TAYLOR, JEFFREY BRUCE, Ph.D. Differential Biomechanical Effects of an ACL Injury Prevention Program in Women's Basketball and Soccer Players (2016)
Directed by Dr. Sandra J. Shultz. 215 pp.

Anterior cruciate ligament (ACL) injury prevention programs are considerably less successful in women's basketball than women's soccer. Despite different sport-specific demands (e.g. more jumping and frontal plane movements in basketball), ACL injury prevention programs have been uniformly administered in both sports and predominantly emphasize improving high-risk biomechanics during sagittal plane tasks. As such, injury prevention programs may not provide the appropriate stimulus to reduce ACL injury risk during the high-risk demands associated with women's basketball. Thus, the purpose of this study was to 1) compare the fundamental movement profiles in adolescent female basketball and soccer players during a variety of jump landing tasks, 2) assess whether an established ACL injury prevention program affects lower extremity biomechanics during sagittal vs. frontal plane and double- vs. single-leg landings, and 3) analyze the extent to which female basketball and soccer players respond differently to a uniform ACL injury prevention program.

A repeated measures experimental design was used in this study. Middle- and high-school aged female basketball and soccer teams were cluster-randomized into intervention (basketball, n=21; soccer, n=27) and control (basketball, n=21; soccer, n=28) groups. Three-dimensional biomechanical analysis was performed during double- and single-leg sagittal and frontal plane tasks before and after the completion of an established 6-week ACL injury prevention program. Biomechanical variables of interest were those that have been theorized to influence ACL injury risk, including hip flexion,

adduction, internal rotation, and knee flexion, abduction, internal rotation and external rotation peak angles, excursions, and peak normalized external joint moments.

At baseline, basketball players exhibited relatively stiff landings, with less hip and/or knee excursion than soccer players. Sport differences were especially apparent as jump landing tasks increased in difficulty, with the single-leg, frontal plane jump landing eliciting the most differences. During this task, basketball players landed with decreased hip adduction angles ($p<.001$), decreased hip flexion ($p=.03$), and knee flexion ($p=.01$) excursions, and increased hip internal rotation ($p=.003$) and relative knee external rotation ($p=.001$) excursions. Additionally, forces differed between sports during the single-leg frontal plane jump landing, with basketball players showing increased knee abduction ($p=.003$) and decreased hip adduction ($p=.001$) and knee external rotation ($p<.001$) moments.

Across sports, no significant biomechanical changes were identified after the training program in any of the sagittal or frontal plane jump landing tasks ($p>.05$). However, limited evidence suggested that biomechanical changes were not the same across all tasks, as participants in the intervention group showed relative decreases in knee abduction moments during the double-leg sagittal plane landing compared to the single-leg sagittal plane landing ($p=.005$). Additionally, women's basketball and soccer players largely exhibited similar biomechanical adaptations after training. No significant differences in biomechanical adaptations were identified between sports during the drop vertical jump, double-leg sagittal plane, or double- and single-leg frontal plane tasks ($p>.05$). During the single-leg sagittal plane jump landing task, basketball players in the intervention group exhibited increased peak knee abduction angles (*p*=.004) and excursions (*p*=.003) after training compared to the basketball control group (*p*=.01) and soccer intervention group (*p*=.01).

These results indicate that the discrepancy in the success of ACL injury prevention programs in basketball and soccer players may not be a function of sport-specific responses to training. Instead, basketball players appear to utilize distinct fundamental movement strategies during a variety of jump landing tasks compared to soccer, and therefore, current prevention programs may not successfully address these sport-specific movement differences. Specifically, basketball players land in potentially higher-risk positions, with decreased levels of hip and knee flexion excursion, and elements of dynamic lower extremity valgus, which are especially prevalent during high level basketball-specific tasks, including jump landings on a single-leg and in the frontal plane. However, 6-weeks of offseason training using a warm-up based ACL injury prevention program does not appear to provide adequate volume or intensity to modify the high-risk movement patterns used during these tasks. Thus, to improve the success of future programs in the basketball population, exercise prescription may need to incorporate higher levels of more intense technique training that emphasizes soft landings during basketball-specific frontal plane and single-leg jumping activities.

DIFFERENTIAL BIOMECHANICAL EFFECTS OF AN ACL INJURY PREVENTION PROGRAM IN WOMEN'S BASKETBALL AND SOCCER PLAYERS

by

Jeffrey Bruce Taylor

A Dissertation Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Greensboro
2016

Approved by

____
Committee Chair

To Stacie:

For the sacrifices you made and your unwavering support to allow me to pursue my goals and dreams. It would not have been possible without you.

To Madelyn and Mark:

You two have been and will forever more be the only inspiration that I need.

APPROVAL PAGE

This dissertation written by JEFFREY BRUCE TAYLOR has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair ______________________________

Dr. Sandra J. Shultz

Committee Members ______________________________

Dr. Randy J. Schmitz

____

Dr. Scott E. Ross

____

Dr. Terry A. Ackerman

____

Dr. Kevin R. Ford

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

ACKNOWLEDGEMENTS

Mom and Dad, for providing the foundation for my success and instilling in me the love of learning and confidence in my abilities.

Dr. Sandra J. Shultz, for your unparalleled mentorship, leadership and commitment to my professional growth. Thank you for all that you have done.

Dr. Kevin R. Ford, for your mentorship and willingness to allow me to pick your brain at even the most inconvenient of times.

My Committee, for your guidance, wisdom and mentorship throughout my time at UNC-G.

My Family, Friends, and Colleagues, for your support that has helped guide me through a challenging few years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are a significant health concern for female athletes (Renstrom et al., 2008) who tear their ACL at a rate 2-4 times higher than males participating in the same sport (Agel, Arendt, & Bershadsky, 2005; Prodromos, Han, Rogowski, Joyce, & Shi, 2007). It is estimated that 3-4% of female athletes participating in multi-directional sports tear their ACL annually (Moses, Orchard, & Orchard, 2012), with basketball and soccer reporting the highest ACL injury rates in team sports (Hootman, Dick, & Agel, 2007). One ACL injury can result in a lifetime cost of $38,000 - $88,000, depending on the severity of injury and method of rehabilitation (Mather et al., 2013). In addition to financial concerns, ACL injuries lead to short-term pain and functional limitations, and long-term sequelae such as the early development of knee joint osteoarthritis, with up to 48% of injured athletes showing signs of joint degradation within 10 years of injury (Oiestad, Engebretsen, Storheim, & Risberg, 2009). Because 70% of these injuries are the result of a non-contact mechanism, it is believed that some ACL injuries may be preventable.

Given the high incidence rates and long-term consequences associated with ACL injury, extensive research has been performed to design and implement ACL injury prevention programs in at-risk populations. These neuromuscular prevention programs have been generally successful in reducing injury rates, especially those produced from a non-contact mechanism (J. B. Taylor, Waxman, Richter, & Shultz, 2015). However, results of ACL injury prevention programs have been inconsistent between women's basketball and soccer players, with significantly higher reductions of injury risk reported in women's soccer than basketball (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007), despite similar injury risk (Agel et al., 2005). It is currently unclear why ACL injury prevention programs have been less successful in women's basketball, though it may be because there has been considerably more research devoted to studying ACL injury prevention programs in women's soccer than women's basketball (O'Brien & Finch, 2014). In the relatively few studies that include women's basketball populations, basketball athletes were administered programs presumably designed for women's soccer, as the same prevention program was uniformly implemented across sports (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; LaBella et al., 2011; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006).

Uniform ACL injury prevention programs for women's basketball and soccer players may not be appropriate, considering the anthropometric and training differences between athletes participating in the two sports. Anthropometrically, women's basketball players are taller (A. Munro, Herrington, & Comfort, 2012; Stanforth, Crim, Stanforth, & Stults-Kolehmainen, 2013; Zakas, Mandroukas, Vamvakoudis, Christoulas, & Aggelopoulou, 1995), and heavier, with greater lean body mass and percent body fat than women's soccer players (Stanforth et al., 2013; Zakas et al., 1995). Biomechanically, they employ different movement strategies for different tasks (Cowley, Ford, Myer, Kernozek, & Hewett, 2006; A. Munro et al., 2012). While women's basketball players exhibit more high-risk strategies during jumping, women's soccer players exhibit more high-risk strategies during cutting (Cowley et al., 2006), indicating that basketball and soccer athletes may be at higher risk during jumping and cutting, respectively. Additionally, women's basketball and soccer require distinct sport-specific demands. While both sports are multi-directional and require rapid changes of direction, basketball players perform 50-70% more frontal plane movements (e.g. lateral shuffling) than soccer players (Ben Abdelkrim, El Fazaa, & El Ati, 2007; Bloomfield, Polman, & O'Donoghue, 2007; Matthew & Delextrat, 2009; McInnes, Carlson, Jones, & McKenna, 1995). This is significant, considering that jump landings in the frontal plane elicit significantly greater knee valgus and less knee flexion than sagittal plane landings (Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2013a, 2013b). Basketball also requires 3-4 times as many jumps per game as women's soccer (Matthew & Delextrat, 2009; Nedelec et al., 2014).

The differences in sport-specific demands and high-risk biomechanical strategies are consistent with the reported differences in the primary mechanism of ACL injury in the two sports. It has been reported that 60% of ACL injuries in women's basketball are the result of a jump landing, with up to 70% occurring during single-leg tasks (Boden, Torg, Knowles, & Hewett, 2009; Krosshaug et al., 2007; Piasecki, Spindler, Warren, Andrish, & Parker, 2003). In soccer, up to 25% of ACL injuries are the result of a jump landing, with greater than 50% resulting from a cutting mechanism (Faude, Junge, Kindermann, & Dvorak, 2005; Piasecki et al., 2003). Despite these differences in intrinsic athlete characteristics, sport-specific demands, and mechanisms of ACL injury in basketball and soccer players, ACL injury prevention programs have been uniformly implemented in both sports (Hewett et al., 1999; LaBella et al., 2011; Pfeiffer et al., 2006). Strength and conditioning research advocates for the specificity of exercise, which contends that training is most effective when the training activities most resemble the sport activity in which improvement is sought (Baechle & Earle, 2000). In this regard, basketball requires more frontal plane movements and single-leg landings than women's soccer, yet close to 90% of the plyometric tasks in ACL injury prevention programs administered to women's basketball players are primarily sagittal plane tasks and around 70% require double-leg landings (Hewett et al., 1999; LaBella et al., 2011; Pfeiffer et al., 2006). While evidence suggests that these injury prevention programs effectively reduce high-risk biomechanics during double-leg sagittal plane tasks (Noyes, Barber-Westin, Smith, Campbell, & Garrison, 2012; Noyes, Barber-Westin, Tutalo Smith, & Campbell, 2013), no changes have been reported during single-leg sagittal plane tasks (Brown, Palmieri-Smith, & McLean, 2014) and no research has examined the biomechanical adaptations during non-sagittal plane tasks. Thus, it is plausible that current ACL injury prevention programs do not provide the correct stimulus to reduce the appropriate high-risk biomechanics during basketball specific activities (frontal plane movements and single-leg jump landing activities).

Statement of Problem

Injury prevention programs are considerably less successful in reducing ACL injury risk in women's basketball players than women's soccer players (Michaelidis &

Koumantakis, 2013; Prodromos et al., 2007) despite similar injury rates amongst the two populations (Agel et al., 2005). Mechanisms of ACL injuries differ between basketball and soccer players, with a higher percentage of ACL injuries in basketball typically occurring during single-leg jump landings (Boden et al., 2009; Piasecki et al., 2003). Sport-specific demands are also considerably different, with basketball requiring more jumping and frontal plane movements than soccer (Ben Abdelkrim et al., 2007; Bloomfield et al., 2007; Matthew & Delextrat, 2009; Nedelec et al., 2014). Despite these differences, injury prevention programs have been uniformly implemented in women's basketball and soccer players, with a majority of the jump training activities emphasizing double-leg sagittal plane movements. Thus, current ACL injury prevention programs may not be providing the appropriate stimulus to reduce high-risk hip and knee biomechanics during single-leg landings and frontal plane movements.

Objective and Hypotheses

The objective of this study was to compare the response of women's basketball and soccer players to an established ACL injury prevention program, as measured by improvements in multi-planar lower extremity biomechanics in double- and single-leg landings during sagittal and non-sagittal plane jump landing tasks after six weeks of training. Specifically, the following hypotheses were examined:

***Hypothesis 1*:** Prior to training, women's basketball athletes will exhibit no significant differences in high-risk hip (flexion, adduction, internal rotation) and knee (flexion, abduction, internal and external rotation) kinematics, but will generate greater hip (flexion, adduction, internal rotation) and knee (flexion, abduction, internal and external rotation) external joint moments during jump landing activities than women's soccer players.

Hypothesis 2**:** After 6 weeks of training, high-risk biomechanics will improve to a larger extent during sagittal plane than frontal plane jump landing tasks.

Hypothesis 3: After 6 weeks of training, there will be no significant differences in biomechanical changes in women's basketball compared to women's soccer players.

Assumptions

1. All participants provided consistent maximum effort during both pre- and post-testing sessions.
2. All participants consistently provided maximum effort and focus during the injury prevention intervention.
3. Three-dimensional biomechanical analysis is reliable and produces accurate kinematic and kinetic measurements through the use of inverse dynamic calculations to model lower extremity motion during jumping tasks.

4. The screening tasks (drop vertical jump, double-leg forward jump, single-leg forward hop, double-leg lateral jump, single-leg lateral hop) adequately simulate high-risk activities of women's basketball and soccer.

Limitations

1. Results from this study are most generalizable to female high school basketball and soccer athletes and caution should be taken when generalizing to other sports, competitive levels, and ages.
2. Results from this study are most generalizable to other multi-component ACL injury prevention programs performed as a warm-up prior to practice or competition.
3. This study does not account for other maturational or hormonal risk factors that may have changed over the course of the intervention.
4. Biomechanical measures were assessed in a standard laboratory setting, which may elicit different kinematic and kinetic measurements than what athletes demonstrate during live competition.
5. Group membership (e.g. intervention vs. control) was cluster randomized, potentially adding some bias to the results.
6. Based on sport-specific demands, the definition of leg dominance may vary between sports.

Delimitations

1. Participants were limited to healthy, high school aged, competitive female athletes whose predominant sport was either soccer or basketball.
2. All athletes were tested in laboratory provided footwear, and tested on the same laboratory surface.

Operational Definitions

Healthy: no injury or surgery to either lower extremity over the past six months; no vestibular disorders.

Soccer Player: athlete whose primary sport is soccer and did not compete in basketball during the previous academic year.

Basketball Player: athlete whose primary sport is basketball and did not compete in soccer during the previous academic year.

High-Risk Biomechanics: kinematic and kinetic strategies that are theorized to place an athlete at risk for ACL injury. High-risk kinematic strategies include greater degrees of hip extension, adduction and internal rotation, and knee extension, abduction and internal/external rotation angles, while high-risk kinetic strategies include decreased levels of hip and knee flexion external moments and greater levels of hip adduction, internal rotation and knee abduction, and internal/external rotation external moments.

Initial Contact: point in time when the vertical ground reaction force exceeds 10 N

Maximal Descent: point in time when the participant's center of mass reaches its lowest position

Toe Off: point in time when the vertical ground reaction force is less than 10 N

Landing Phase: period of time from initial contact to maximal descent of the center of mass

Leg Length: distance from the most superior prominence of the greater trochanter to the most distal prominence of the lateral malleolus

Truncated Foot Length: distance between posterior calcaneus and first metatarsophalangeal joint

Arch Height Index: ratio of the height of the dorsum of the foot to the truncated foot length measured in sitting and standing

Triple Hop for Distance Test: a single-leg power test in which the participant performs 3 consecutive forward jumps for maximal distance on the same leg

Double-Leg Forward Jump: task that involves the participant jumping forward off two legs from a distance equal to their leg length away from the force plates, performing a double-leg landing followed by an immediate maximal vertical jump, reaching for a target with both hands

Single-Leg Broad Hop: task that involves the participant jumping forward off one leg from a distance equal to one-half of leg length away from the force plates, landing on the same leg, followed by an immediate maximal vertical jump, reaching for a target with the contralateral hand.

Double-Leg Lateral Jump: task that involves the participant jumping laterally off two legs from a set distance away (equal to one-half of leg length plus 24 inches) from the force plates, landing simultaneously on both legs, followed by an immediate maximal vertical jump, reaching for a target with both hands.

Single-Leg Lateral Hop: task that involves the participant jumping laterally off one leg from a set distance away (equal to one-half of leg length plus 24 inches) from the force plates, landing on the opposite leg, followed by an immediate maximal vertical jump, reaching for a target with the contralateral hand.

Program Compliance: percentage of training sessions in which the athlete participated, relative to the number of training opportunities

Dominant Limb: the limb that generates the longest triple-hop for distance score.

Sport Participation History: prior years of participation in basketball and soccer

Predictor/Independent Variables

Training group: membership (cluster randomized) into training or control groups

Sport group: predominant sport of participation (basketball or soccer)

Dependent Variables

Lower extremity biomechanics during the landing phase of jump landing activities, including:

> *Knee Flexion Kinematics:* sagittal plane flexion angle of the tibia relative to the femur [peak level and excursion (value at initial contact – peak value)] during the landing phase

Knee Flexion External Moment: peak torque produced promoting knee flexion during the landing phase

Knee Abduction Kinematics: frontal plane abduction angle of the tibia relative to the femur [peak level and excursion (value at initial contact - peak value)] during the landing phase

Knee Abduction External Moment: peak torque produced promoting knee abduction during the landing phase

Tibial Rotation Kinematics: transverse plane internal and external rotation angles of the tibia relative to the femur [peak level and excursion (value at initial contact - peak value)] during the landing phase

Tibial Rotation External Moment: peak torque produced promoting tibial internal and external rotation during the landing phase

Hip Flexion Kinematics: sagittal plane flexion angle of the femur relative to the pelvis [peak level and excursion (value at initial contact – peak value)] during the landing phase

Hip Flexion External Moment: peak torque produced promoting hip flexion during the landing phase

Hip Adduction Kinematics: frontal plane adduction angle of the femur relative to the pelvis [peak level and excursion (value at initial contact - peak value)] during the landing phase

Hip Adduction External Moment: peak torque produced promoting femoral adduction during the landing phase

Hip Internal Rotation Kinematics: transverse plane internal rotation angle of the femur relative to the pelvis [peak level and excursion (value at initial contact - peak value)] during the landing phase

Hip Internal Rotation External Moment: peak torque produced promoting femoral internal rotation during the landing phase

CHAPTER II

LITERATURE REVIEW

Due to the alarming incidence of ACL injury in female athletic populations, sports medicine professionals have developed, implemented and researched the effectiveness of primary prevention programs in at-risk athletes. These programs have been predominantly designed to target female soccer (Gilchrist et al., 2008; Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Kiani et al., 2010; Mandelbaum et al., 2005; Soderman, Werner, Pietila, Engstrom, & Alfredson, 2000; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008; Walden, Atroshi, Magnusson, Wagner, & Hagglund, 2012) and handball (Myklebust et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen et al., 2005) athletes and the majority have been reported to successfully reduce the risk of ACL injury. Despite ACL injury rates in women's basketball being comparable to those in women's soccer (Prodromos et al., 2007), no prevention program has been designed specifically for women's basketball players. Moreover, among previous programs that have been tested in women's basketball populations, results suggest that prevention programs are less effective in women's basketball than soccer (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007), possibly because the programs have not been designed for the sport-specific demands of women's basketball. Research is therefore needed to determine why current prevention programs are less successful in women's basketball so that appropriate basketball-specific programs can be developed. The following literature review will attempt to present and summarize the current evidence regarding ACL injury prevention programs and their relative effectiveness in women's basketball compared to women's soccer. To elucidate the need for future research on ACL injury prevention in women's basketball, this review will also compare these sports on the 1) epidemiology of ACL injury, 2) mechanism of injury, 3) sport-specific demands, and 4) physical and biomechanical characteristics of their competing athletes.

ACL Injury Prevention Programs

The effectiveness of numerous ACL injury prevention programs has been studied in athletes that participate in various multi-directional sports, yet a majority have focused specifically on soccer or handball (Gilchrist et al., 2008; Heidt et al., 2000; Kiani et al., 2010; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Soderman et al., 2000; Steffen et al., 2008; Walden et al., 2012). These programs range from 10-90 minutes in duration and have been implemented either as a warm-up prior to practice or competition (Gilchrist et al., 2008; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Pfeiffer et al., 2006; Soderman et al., 2000; Steffen et al., 2008; Walden et al., 2012), or as a pre-season training program (Heidt et al., 2000; Hewett et al., 1999). Program frequencies also vary, ranging from once per week (Kiani et al., 2010; Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Steffen et al., 2008) to daily (LaBella et al., 2011; Soderman et al., 2000; Steffen et al., 2008), and in some cases the frequency is reduced as the program transitions from a pre-season to an in-season phase (Kiani et al., 2010; Myklebust et al., 2003; Olsen et al., 2005; Petersen et al., 2005; Soderman et al., 2000; Steffen et al., 2008). Along with the differences in training durations, ACL prevention programs are wide-ranging in exercise prescription, utilizing a combination of strength, explosive, proprioceptive, flexibility and agility training activities at diverse intensities (J. B. Taylor, Waxman, et al., 2015). While the majority of these prevention programs have been found effective in reducing non-contact injury risk (OR = 0.35, 95% CI 0.23,0.54), the ideal combination of training components, duration and intensity is not well understood (J. B. Taylor, Waxman, et al., 2015).

Comparative Effectiveness of ACL Injury Prevention Programs in Basketball and Soccer

ACL injury prevention programs result in varying levels of injury risk reduction in different sports (Gagnier, Morgenstern, & Chess, 2013; Michaelidis & Koumantakis, 2013; Prodromos et al., 2007; Yoo et al., 2010). In soccer, ACL prevention programs yield a more protective effect than in any other sport (Gagnier et al., 2013; Yoo et al., 2010). More specifically, a meta-analysis reported that ACL injury prevention programs significantly reduced the risk of ACL injury in soccer (OR = 0.26, 95% CI 0.13, 0.50, p = < .001), yet were not successful in basketball (OR = 2.57, 95% CI 0.74, 8.88, p = .15) (Prodromos et al., 2007) and these results were confirmed in a more recent systematic review (Michaelidis & Koumantakis, 2013). The lack of program success in women’s basketball is especially concerning, considering that ACL injury incidence rates are similar in women's soccer and basketball (Agel et al., 2005; Prodromos et al., 2007).

One explanation for differing rates of effectiveness may be that ACL injury prevention programs have not been as extensively studied in women's basketball. In a recent systematic review that included a total of 13 published studies on ACL injury prevention programs (J. B. Taylor, Waxman, et al., 2015), only three studies administered these programs to a sample of female basketball athletes (Hewett et al., 1999; LaBella et al., 2011; Pfeiffer et al., 2006) while ten were administered to soccer players (Gilchrist et al., 2008; Heidt et al., 2000; Hewett et al., 1999; Kiani et al., 2010; LaBella et al., 2011; Mandelbaum et al., 2005; Pfeiffer et al., 2006; Soderman et al., 2000; Steffen et al., 2008; Walden et al., 2012). This trend is also apparent in more general injury prevention programs, as 50% of current research is devoted to soccer, with only 8% to basketball (O'Brien & Finch, 2014). Of the three ACL injury prevention programs administered to basketball players, they were also implemented in a sample of soccer athletes without modification. Table 2.1 displays the results of each of the studies performed uniformly in both basketball and soccer populations. This table suggests that ACL injury risk reduction is consistently higher in soccer compared to basketball players.

Table 2.1 Effectiveness of Prevention Programs on ACL Injury Risk Reduction in Women's Basketball and Soccer Populations. Odds ratios reported were calculated based on data reported in manuscript (Hewett et al., 1999; Pfeiffer et al., 2006) and retrieved from contacting the corresponding author (LaBella et al., 2011). (PS – player seasons)

Study	**Sport**	**Group**	**PS**	**Total ACL Tears**	**Odds Ratio [95% CI]**
Hewett et al. (1999)	Basketball	Intervention	84	2	1.51 [0.25,9.2]
		Control	189	3	
	Soccer	Intervention	97	0	0.39 [0.02,8.26]
		Control	293	2	
LaBella et al. (2011)	Basketball	Intervention	416	2	0.40 [0.08,2.08]
		Control	421	5	
	Soccer	Intervention	321	0	0.35 [0.01,8.52]
		Control	334	1	
Pfeiffer et al. (2006)	Basketball	Intervention	191	3	2.53 [0.42,15.28]
		Control	319	2	
	Soccer	Intervention	189	0	0.43 [0.02,10.57]
		Control	244	1	

It is not entirely clear why these programs do not result in similar levels of injury risk reduction in women's basketball and soccer, particularly when one considers that the risk of ACL injury prior to any intervention is comparable in the two sports (Agel et al., 2005; Arendt & Dick, 1995). In general, these programs are reported to improve neuromuscular function, including quadriceps and hamstrings strength (Noyes & Barber Westin, 2012). Additionally, improvements in biomechanics, such as less knee abduction and increased knee flexion angles and excursions have been reported in women's basketball and soccer players after completion of an ACL injury prevention program during bilateral, sagittal plane jump landing activities (Lim et al., 2009; Noyes et al., 2012; Noyes et al., 2013; Pollard, Sigward, Ota, Langford, & Powers, 2006). However, other studies suggest that high-risk biomechanics during unilateral landings have not improved after completing injury prevention programs that emphasized neuromuscular or core stability training (Brown et al., 2014), and to date, no comparisons have been made between the neuromuscular or biomechanical improvements seen in women's basketball and soccer athletes to determine if they respond differently to training stimuli provided in these prevention programs.

It is also possible that differing levels of effectiveness of ACL injury prevention programs are due to the interventions being designed more specific to women's soccer than basketball. Of the three prevention programs that have been tested in both women's basketball and soccer athletes, each used multiple training components, yet emphasized explosive jump training, with lesser emphasis on strength and agility training. While plyometric training would seem consistent with the jumping demands of basketball, closer examination of the specific plyometric activities prescribed in these programs reveal a distinct lack of emphasis placed on single-leg landings and activities performed outside of the sagittal plane (e.g. lateral shuffling/jumping). When considering all of the plyometric activities in the three aforementioned ACL injury prevention programs (Hewett et al., 1999; LaBella et al., 2011; Pfeiffer et al., 2006), it appears as though only 28% of the training exercises involved single-leg landings, 12% of the tasks were directed in the frontal plane and 5% utilized a combination of both. As will be discussed in subsequent sections of this review, basketball requires substantially more single-leg jump landings and frontal plane movements during an average competition than soccer (Ben Abdelkrim et al., 2007; Bloomfield et al., 2007; Matthew & Delextrat, 2009; McInnes et al., 1995; Nedelec et al., 2014; Reilly & Thomas, 1976). This may indicate that current ACL injury prevention programs have not targeted the types of activities where high-risk biomechanics are most likely to occur in women's basketball, thus not adequately improving protection about the knee during the most common injurious activities.

Summary

ACL injury prevention programs have been more successful in reducing injury risk in women's soccer than basketball (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007); therefore, as currently designed, these prevention programs may not be as appropriate for use in women's basketball. Further research is needed to identify the reasons for differing effectiveness of injury risk reduction in the two sports. Injury prevention programs are typically designed using a four-step cyclical paradigm: 1) establish the extent of the problem, 2) establish the etiology and mechanisms of injury, 3) introduce the intervention, and 4) assess the effectiveness of the intervention by returning to step one (van Mechelen, Hlobil, & Kemper, 1992). Considering the concerning ACL injury rates and lack of effective preventative efforts in women's basketball, the remainder of this review will use this paradigm as an organizational framework. First the epidemiology (Step 1) and mechanism (Step 2) of ACL injury in women's basketball and soccer will be compared to help delineate possible reasons for differing effectiveness of ACL prevention programs in these two sports, followed by justification for further research and development of basketball-specific ACL injury prevention programs (Step 3).

ACL Injury Incidence Rates

In basketball, ACL injury rates differ by age, competition level and gender. Epidemiological studies have published incidence rates ranging from 0.18-0.39 injuries per 1000 athletic exposures (AE) (Agel et al., 2005; Arendt & Dick, 1995; Gomez, DeLee, & Farney, 1996; Hootman et al., 2007; Mihata, Beutler, & Boden, 2006; Mountcastle, Posner, Kragh, & Taylor, 2007; Vauhnik et al., 2011). The wide range of incidence rates may be attributed to differences in sample populations, as age and competitive level can affect an athlete's physical maturity or the intensity at which the game is played (Brito et al., 2011; Schmikli, de Vries, Inklaar, & Backx, 2011).

Age and Competitive Levels

ACL injury incidence rates in women's basketball are reported to be highest in collegiate populations. This is consistent with epidemiological findings in the general population that suggest ACL injury rates peak in women between the ages of 20-24 years of age (Gianotti, Marshall, Hume, & Bunt, 2009). For the purpose of this review, all collegiate levels have been classified together, as research indicates similar incidence rates between competitive levels of the National Collegiate Athletic Association (NCAA) (Harmon & Dick, 1998). Studies using the NCAA Injury Surveillance System have reported injury rates from 0.23-0.32 ACL tears per 1000 AE, with injuries as the result of a non-contact mechanism accounting for 0.16 tears per 1000 AE (Agel et al., 2005; Arendt & Dick, 1995; Hootman et al., 2007; Mihata et al., 2006). These injury rates have been tracked over the past three decades, with results indicating that injury rates have remained relatively stable, despite the implementation of ACL injury prevention programs (Agel et al., 2005). Two separate studies have examined intercollegiate basketball players of similar age level at individual military institutions, reporting incidence rates of 0.39 and 0.48 ACL tears per 1000 AE (Gwinn, Wilckens, McDevitt, Ross, & Kao, 2000; Mountcastle et al., 2007). These rates are considerably higher than rates reported in a traditional collegiate athletic setting, but may be influenced by the significant additional physical demands associated with attending a military institution.

In professional women's basketball players, ACL injury incidence rates of 0.18-0.20 ACL injuries per 1000 AE, have been reported (Trojian & Collins, 2006; Vauhnik et al., 2011). When evaluating injuries during game situations exclusively, incidence rates climb to 0.40 injuries per 1000 game exposures, which may be attributed to higher intensity levels when compared to practice situations (Deitch, Starkey, Walters, & Moseley, 2006). Comparable data for ACL injury rates in relation to game exposures at other competitive levels is not available. Overall low incidence rates in professional women's basketball may be attributed to the sports medicine staff dedicated to help meet training needs, which may effectively reduce the risk of injury in this population. However, despite relatively low incidence rates, injury risk continues to be concerning because 14.4% of females entering professional basketball have previously undergone ACL surgical reconstruction (McCarthy, Voos, Nguyen, Callahan, & Hannafin, 2013). Although no known study to date has evaluated the risk of re-tear in female professional basketball players, prior ACL rupture has been reported as a risk factor in other populations, suggesting up to 25% of surgically reconstructed patients may suffer another ACL injury in the subsequent 12 months (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012). Further, the low incidence rates in professional women's basketball should be interpreted cautiously, as sample sizes are relatively low and may be biased, considering the relative skill level and health needed to sign a professional contract.

ACL injury incidence rates in female high school basketball players have not been as extensively researched as other competitive levels. Available evidence suggests the lowest ACL injury rates at this level of competition, with incidence rates as low as 0.10 tears per 1000 AE reported in a 2007 meta-analysis (Prodromos et al., 2007). These lower rates are surprising, considering reports that ACL injuries begin to dramatically increase at the ages of 14-17 in female athletes (Csintalan, Inacio, & Funahashi, 2008).

Despite the lower incidence rates in this age group, ACL rupture is still a major concern, as one study reported that ACL tears account for 44% of all injuries that require surgery amongst high school women's basketball players (Gomez et al., 1996). As such, these low rates may also reflect a significantly lower playing intensity in women's high school basketball compared to other competitive levels; therefore, creating less risky, injurious situations.

Moreover, these lower rates in high school basketball players may suggest an ideal time to intervene, as ACL injury prevention programs are reported to be considerably more successful in females between the ages of 14-18 [odds ratio (OR) = 0.28, 95% confidence interval (CI): 0.18,0.42], than 18-20 (OR = 0.48, 95%CI 0.21,1.07) and older than 20 (OR = 1.01, 95% CI 0.62,1.64) (Myer, Sugimoto, Thomas, & Hewett, 2013). This may be due to the sex-divergent physical characteristics that begin to emerge in the younger age group. During puberty, females develop greater fat mass and less relative fat-free mass than their male counterparts (Loomba-Albrecht & Styne, 2009), and between the ages of 14-18 become more reliant on their quadriceps musculature (Sigward, Pollard, & Powers, 2012), and land with greater levels of knee abduction (Hewett, Myer, & Ford, 2004; Schmitz, Shultz, & Nguyen, 2009) and knee extension (Hass et al., 2003; Hass et al., 2005; Yu et al., 2005), which may contribute to a higher risk of ACL injury (Hewett et al., 2005). ACL injury prevention programs have been reported to alter movement strategies by limiting the increases in knee abduction moments and range of motion that typically progress during these ages (Otsuki, Kuramochi, & Fukubayashi, 2014; Schmitz et al., 2009; Yu et al., 2005), which may ultimately be responsible for the more effective injury prevention outcomes. While further research is needed to more clearly understand the relationships of age, competition level, and intensity level with ACL injury in women's basketball players, preventative efforts may be most efficacious when directed towards the adolescent population.

Comparative Injury Rates in Basketball and Soccer

Basketball and soccer represent two of the top three women's sports with the highest ACL injury incidence rates in American collegiate sports (Agel et al., 2005; Hootman et al., 2007). Information from the NCAA Injury Surveillance System likely provides the most appropriate comparison between the sports since data has been obtained in a large athletic population over multiple years. Meta-analysis results of pooled ACL injury incidence rates in the collegiate population has been reported to be 0.29 and 0.32 ACL tears per 1000 AE in the basketball and soccer populations, respectively; however, these rates accounted for all ACL injuries and did not specifically parse out injuries from a purely non-contact mechanism (Prodromos, et al., 2007). Agel et al. (2005) examined both total ACL injuries and non-contact ACL injuries in collegiate women's basketball and soccer and reported that soccer players suffered significantly (p=.04) more total ACL injuries (0.31 per 1000 AE) than basketball players (0.27 per 1000 AE), yet women's basketball players suffered significantly (p=.008) more non-contact ACL injuries (0.16 per 1000 athletic exposures) than soccer players (0.13 per 1000 athletic exposures) throughout the same timeframe. The fact that ACL injury incidence rates are similar in women's basketball and soccer is significant, highlighting the need for effective preventative efforts in both populations. Though incidence rates are similar, ACL injuries may be considered more severe in women's basketball than soccer, as basketball athletes are 1.28 and 1.23 times more likely to incur an associated lateral meniscus tear or cartilage damage, respectively (Granan, Inacio, Maletis, Funahashi, & Engebretsen, 2013). Considering the comparable incidence rates and severity of ACL injuries in women's basketball and soccer and the lack of effectiveness of ACL prevention programs in women's basketball, further focused research towards ACL prevention in women's basketball is warranted.

Gender Differences in Injury Rate by Sport

Differences in ACL injury rates between males and females have been extensively examined, with females generally reported to have 2-4 times higher rates than males (Prodromos et al., 2007). Studies utilizing the NCAA Injury Surveillance System report female to male basketball injury rates to range from 3.28-4.14 times higher in females for all ACL injuries, and 4.59 times higher in females for non-contact injuries alone (Agel et al., 2005; Arendt & Dick, 1995; Hootman et al., 2007). Gender discrepancies in injury rates are comparable between sports, but somewhat higher in basketball (female-male ratio = 3.50) than soccer (female-male ratio = 2.67) (Prodromos et al., 2007).

Summary

Though ACL injury incidence rates are high in all competitive levels of women's basketball, they are highest in collegiate basketball. However, due to the divergent physical and biomechanical characteristics that occur during maturation, high school may be the most appropriate time to implement prevention strategies in women's basketball. Additionally, ACL incidence rates in women's basketball are comparable to and equally concerning as those in women's soccer, warranting further research that focuses on targeted prevention programs for ACL injury that are effective in both athletic populations.

Mechanism of ACL Injury

Two-thirds of all ACL injuries result from cutting, landing, or other non-contact mechanisms (Arendt & Dick, 1995; Krosshaug et al., 2007). These activities are common in both basketball and soccer, which require athletes to react to unanticipated events and respond to game situations to gain an athletic advantage. Cutting and jump landings demand deceleration and directional changes, whether vertically or horizontally, placing athletes at higher risk of injury. Further, due to the associated increases in intensity and unpredictability during game situations, female athletes are significantly more likely to suffer an ACL injury in a game compared to a practice setting (Hootman et al., 2007). The following section will review previous research detailing the typical mechanisms of ACL injury in women's basketball and compare these mechanisms to those most commonly found in soccer.

Basketball

Similar to other sports, a majority of ACL tears in women's basketball players occur via a non-contact mechanism (Agel et al., 2005). Results of video analysis have provided initial data regarding the exact mechanism of injury in basketball, though cautious interpretation is warranted due to the small sample sizes used in these studies (Boden et al., 2009; Krosshaug et al., 2007). Jump landings have been observed in up to 86.7% of ACL injuries occurring in female basketball players with only 13% the result of cutting (Krosshaug et al., 2007). Additionally, up to 90% of these injuries are sustained during a single-leg activity, as opposed to a double-leg activity (Boden et al., 2009). In some cases, what may technically be considered a double-leg landing may actually be more representative of a single-leg landing, considering that significant landing asymmetry (timing, kinematics, kinetics) has been reported in female basketball players while attempting double-leg landings (Herrington, 2011).

In general most injuries occur while attacking, as opposed to defending, and the most frequent activity causing injury in basketball practice is the result of rebounding (Krosshaug et al., 2007; Powell & Barber-Foss, 2000). Additionally, the physical nature of the game may factor into the etiology of these injuries. Video analysis of ACL injuries show that despite the absence of physical contact from an opposing player at initial ground contact, up to 50% of injured female basketball athletes were either part of a collision or pushed immediately prior to injury and a high percentage of injuries occurred with another player in a surrounding one-meter radius (Krosshaug et al., 2007). These physical demands associated with basketball may be important, as it is consistent with evidence from the skiing literature that suggests that reacting to external perturbations is the main cause of ACL injury during landing activities (Gerritsen, Nachbauer, & van den Bogert, 1996).

Comparison to Soccer

Only one study has directly compared the mechanism of ACL injury in basketball and soccer (Piasecki et al., 2003). A survey of basketball (n=85) and soccer players (n=18) that were to undergo ACL reconstruction reported that ACL injuries were jumping related in 60% of high school and 46% of amateur basketball athletes (Piasecki et al., 2003). In comparison, female soccer players suffered ACL injuries as the result of a jump landing only 25% of the time in high school athletes and 0% of the time in amateur athletes (Piasecki et al., 2003). Other evidence supports these findings, with reports that cutting is the predominant mechanism of injury in soccer, accounting for over 60% of non-contact ACL injuries (Faude et al., 2005).

These findings suggest that jump landings are the predominant mechanisms of ACL injury in basketball and cutting may account for most of the ACL injuries in soccer. Because the mechanisms are different, the precipitating risk factors may also be different, and therefore call for ACL injury prevention programs to be designed for the sport. For example, because ACL injuries occur more commonly during jump landing activities in women's basketball, the ability to limit abnormal forces at the knee during jump landings may be more important to assess and train in women's basketball players than soccer players. Thus, ACL injury prevention programs designed for one sport may not fully address the high-risk biomechanics associated with ACL injury of another. Despite the potential need for sport-specific intervention, previously designed ACL injury prevention programs have been largely designed for women's soccer athletes, yet uniformly implemented without modification in women's basketball. Future programs may be more effective if modified to account for the predominant mechanisms of injury and risk factors associated with the sport.

Factors Associated with the Mechanism of ACL Injury

While the distinct mechanisms of ACL injury in women's basketball and soccer players may in part explain the differing efficacies of ACL injury prevention programs in these athletes, it is also important to identify the specific risk factors associated with the different mechanisms of injury in these two sports. After reviewing the sport-specific demands of women's basketball and soccer, the following section will review risk factors that have been reported to be associated with ACL injury in women's basketball, including physical characteristics and movement strategies, making direct comparisons to women's soccer when possible.

Sport-specific demands. The activity demands of basketball encompass repetitive unanticipated movements requiring high- to maximum-intensity efforts such as sprinting and jumping, moderate-intensity efforts such as running or shuffling, and low-intensity efforts such as jogging. While not specific to females, researchers have quantified these movements through computerized time-motion analysis of video footage

(Ben Abdelkrim et al., 2007; Matthew & Delextrat, 2009; McInnes et al., 1995). During competition, on average, basketball athletes have been found to change direction every 2.0-2.8 seconds (Matthew & Delextrat, 2009; McInnes et al., 1995). High-intensity activities occur every 21 seconds (McInnes et al., 1995), which are significant because these events typically involve higher speeds and power, generating a higher-risk situation that is more conducive to ACL injury. Table 2.2 displays the frequency, relative frequency and duration of high-intensity activities that basketball players perform during competition (Ben Abdelkrim et al., 2007; Matthew & Delextrat, 2009; McInnes et al., 1995). Across the three studies, the relative frequencies illustrate that basketball players perform 4.5-5.9 high-intensity activities per minute of game action, consisting of 1.7-2.7 shuffles, 1.6-2.8 sprints, and 1.0-1.3 jumps.

Table 2.2. Frequency and Duration of Specific Activity Demands During Competitive Basketball (Relative Frequency= Number of Movements per Minute Played, s= Seconds)

		McInnes et al. (1995)	**Ben Abdelkrim et al. (2007)**	**Matthew & Delextrat (2009)**
Population	Skill Level Size and Sex	professional n = 8 males	high school n = 38 males	professional n = 9 females
Jumping (mean±SD)	Relative Frequency	1.28	1.24	1.00
	Frequency	46 ± 12	44 ± 7	35 ± 11
	Duration	0.9s ± 0.1	1.0s ± 0.1	--
	% of Live Time	--	2.1% ± 0.3	--
Sprinting (mean±SD)	Relative Frequency	2.84	1.55	1.67
	Frequency	105 ± 52	55 ± 11	49 ± 17
	Duration	1.7s ± 0.2	2.1s ± 0.1	--
	% of Live Time	--	5.3% ± 0.8	--
Agility/Shuffling (High-intensity) (mean±SD)	Relative Frequency	1.73	2.66	1.87
	Frequency	63 ± 33	94 ± 16	58 ± 19
	Duration	2.0 ± 0.4	2.0s ± 0.2	--
	% of Live Time	--	8.8% ± 1.0	--

Comparison to soccer. Both basketball and soccer are considered intermittent, endurance sports with a strong multi-directional component that require similar frequencies of high-intensity running; however, other activity demands are considerably different between the two sports (Bangsbo, Norregaard, & Thorso, 1991; Mohr, Krustrup, & Bangsbo, 2003). On average, basketball players change direction or intensity more frequently than soccer players (2.0-2.8 versus 4.5 seconds), lending to more recurrent bouts of deceleration, thus more frequently placing the athlete in potentially injurious situations (Matthew & Delextrat, 2009; McInnes et al., 1995). Additionally, basketball requires larger vertical demands, as soccer players average only 10 jumping activities per game, which is approximately 3-4 times less over the course of a match than an average basketball player (Ben Abdelkrim et al., 2007; Matthew & Delextrat, 2009; McInnes et al., 1995; Nedelec et al., 2014). Soccer players also engage in less lateral shuffling during live game action compared to basketball players (9% vs. 46% of purposeful movement), suggesting that larger amounts of frontal plane movement occurs throughout a basketball game (Bloomfield et al., 2007; Matthew & Delextrat, 2009). As no prior studies have examined the landing patterns of jumping activities during game situations, future research should consider recording the plane of movement and number and ratio of single- to double-leg landing in these two sports, as this may further elucidate why the mechanisms of ACL injury are different between sports and aid the design of future ACL prevention programs.

Environmental Considerations. In addition to differences in biomechanical and physiological demands, basketball and soccer players face different environmental risk factors that may influence ACL injury. One such factor is differing shoe-surface interfaces (Livesay, Reda, & Nauman, 2006; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2003). Basketball is traditionally played indoors on a hardwood floor, demanding athletes to wear flat, rubber-soled footwear. Conversely, soccer is played outdoors on a natural grass or synthetic turf field, requiring athletes to account for weather, as well as surface variables, when choosing footwear (typically cleats). While researchers have investigated the optimal shoe-surface interface coefficient, taking into account both performance and injury prevention benefits and paying special attention to the effect of cleats on artificial and natural turf surfaces, little has been researched on the basketball court (Bentley, Ramanathan, Arnold, Wang, & Abboud, 2011; Drakos et al., 2010; Olsen et al., 2003). Research in this area is warranted considering that larger magnitudes of friction at the shoe-surface interface translate to the knee in the form of ACL strain (Drakos et al., 2010).

Finally, differences exist between the size of basketball and soccer playing surfaces. At the international-professional level, a basketball court measures 420m^2 (28m x 15m), compared to a soccer field of 7350m^2 (105m x 70m). A soccer game is played with 22 players on the field, compared to 10 in basketball. When accounting for the amount of playing surface per player, basketball athletes (43.7m^2) have a considerably lower surface area to player ratio than soccer players (334.1m^2), which may lead to more physical interactions and less space for competitors to maneuver. This surface area to player ratio may have implications for more repetitive change of direction and deceleration maneuvers during basketball competition. This is significant because the addition of a defender has been shown to alter lower extremity biomechanics by promoting larger peak knee valgus angles, thereby potentially placing athletes at higher-risk of injury (McLean, Lipfert, & van den Bogert, 2004). Therefore, whether evading a defender or receiving an unanticipated perturbation due to the physicality of the game, the size of the playing surface may have important implications on injury risk in women's basketball and may need to be considered while designing future basketball-specific ACL injury prevention programs.

Physical characteristics. Activity demands that define a sport may attract certain athletes in order to best exploit their body-type and physical strengths. For example, taller athletes are customarily recruited to play basketball because of the advantage their height may provide. Further, because sports require differing activity-related demands, athletes' training programs are tailored to achieve optimal athletic performance by emphasizing those components more prevalent or important in their sport. These factors may lead to distinct physical characteristics between athletes participating in different sports. A study consisting of collegiate athletes from four sports with distinct sport-specific demands reported significant differences in upper and lower extremity strength and muscle power between athletes of the four sports (Izquierdo, Hakkinen, Gonzalez-Badillo, Ibanez, & Gorostiaga, 2002). Moreover, sport activities differ in the repetitive loads placed on the lower extremity, suggesting that sport-specific training and competition may produce distinct physiological or neuromuscular adaptations over time such as differences in muscle cross-sectional area, fiber type distribution and muscle mechanics (Izquierdo et al., 2002). Women's basketball and soccer athletes have been reported to differ in their physical characteristics (Stanforth et al., 2013), which may be attributed to their pre-existing body type that attracted them to their sport, or characteristics that have developed as the result of competition and training for different sport-specific demands. Whether these types of neuromuscular or physical differences represent sport-specific risk factors that may explain disparities in the effectiveness of ACL injury prevention programs on reducing injury rates is not currently known.

Comparison of basketball and soccer players. Anthropometrically, basketball players are found to be consistently taller than soccer players (A. Munro et al., 2012; Stanforth et al., 2013; Zakas et al., 1995). While added height may give a basketball player an athletic advantage due to the vertical demands inherent with the game, height has been implicated as a risk factor for knee injury (Vauhnik et al., 2008). The exact mechanism by which height may increase injury risk is unknown. Theoretically, a longer femur and tibia may provide larger lever arms acting on the knee joint, resulting in higher forces at the knee during sport-related activities that may be magnified during abnormal movement strategies such as lower extremity dynamic valgus. However, height has been reported to be negatively correlated with anterior knee laxity (Vauhnik et al., 2009), suggesting taller athletes are at less risk of ACL injury because anterior knee laxity measurements one standard deviation above the mean has been reported as predictive of future ACL injury (Uhorchak et al., 2003). Further investigation of height as a risk factor for injury, especially in women's basketball athletes, is needed.

Basketball players are also reported to be heavier, with both greater lean body mass and percent body fat (Stanforth et al., 2013; Zakas et al., 1995). Because of this, it is logical to hypothesize that women's basketball players may exhibit higher body mass index (BMI) values than soccer players, although no significant difference between basketball and soccer players has been reported with respect to BMI (A. Munro et al., 2012). Differences in body composition may have implications for ACL injury, as a higher BMI has been associated with increased ACL injury risk (Uhorchak et al., 2003), suggesting that larger ratios of body fat to lean mass may lead to less muscular control of the knee joint. Additionally, higher levels of lean mass surrounding the knee joint may provide a protective effect on the ACL through reduced levels of multiplanar knee laxity (Shultz, Pye, Montgomery, & Schmitz, 2012).

There are mixed results comparing sagittal plane thigh strength in female basketball and soccer players. After normalizing for body mass, no significant differences have been reported between basketball and soccer players in quadriceps or hamstrings isokinetic peak torque at 60°, 120°, or 180° sec^{-1} (Rosene, Fogarty, & Mahaffey, 2001; Zakas et al., 1995). However, a comparison of the isokinetic strength of court (basketball and volleyball) and field (soccer) athletes reported significantly lesser hamstrings strength and hamstrings to quadriceps strength ratio of the dominant leg in court athletes relative to field athletes (Cheung, Smith, & Wong del, 2012). This is important because isolated contractions of the quadriceps muscle group can produce relatively high levels of anterior tibial translation, placing increased force through the ACL (Draganich & Vahey, 1990; Durselen, Claes, & Kiefer, 1995; Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986). Conversely, the hamstrings provide a protective, posteriorly directed force, limiting anterior tibial translation during co-contraction with the quadriceps (Draganich & Vahey, 1990). While no studies have recommended an optimal quadriceps to hamstrings strength ratio in these athletes, greater quadriceps to hamstrings ratios have traditionally been thought to place an athlete at an increased risk of ACL injury (Myer et al., 2009). No definitive conclusions about differences in thigh strength can be taken from these studies, as sample sizes were small and only one study addressed differences in females.

Movement strategies. Since an athlete's physical characteristics may be indicative of their sport participation or training history, it is logical that athletes of different sports may also employ distinct movement strategies. The following section will first summarize the movement strategies that are considered high-risk for ACL injury. Studies performed specifically on basketball players that have identified high-risk movement patterns will then be discussed, followed by an appraisal of prior studies that compare women's basketball and soccer players.

Movement strategies predictive of ACL injury. Researchers have attempted to identify biomechanical risk factors of ACL injury through a variety of methods. This section will review and examine studies with prospective designs and those that used observational video analysis of injurious events, as these may provide the most accurate evidence regarding the biomechanical risk factors at the time of injury, specifically focusing on two movement strategies that have been comprehensively examined: 1) dynamic lower extremity valgus, and 2) shallow knee flexion angles.

Dynamic Lower Extremity Valgus. Larger levels of dynamic lower extremity valgus defined as a combination of hip adduction, hip internal rotation, knee abduction, knee external rotation and ankle inversion, have been implicated as a risk factor for ACL injury. A prospective study screened 205 female high school athletes participating in basketball, soccer and volleyball prior to their competitive seasons using a drop vertical jump (DVJ) task and tracked ACL injuries throughout the subsequent season (Hewett et al., 2005). Statistical analysis revealed that knee abduction measures including maximum knee abduction angle, knee abduction angle at initial contact (IC), and knee abduction external moments were significant predictors of subsequent ACL injury, making these characteristics important variables to consider when designing prevention programs targeting at-risk athletes. While these results are based on only nine ACL tears and only two in a basketball population, this study is the only prospective study to link three-dimensional biomechanics to ACL injury risk. Further credence for the impact of knee abduction on ACL injury risk is also supported by computer simulation models which suggest that anterior tibial translation alone may not be strong enough to cause rupture of the ACL, yet anterior tibial translation in combination with abduction or adduction loads can produce enough injurious force to tear the ACL (McLean, Huang, Su, & Van Den Bogert, 2004).

Knee abduction has also been implicated as a mechanism of ACL injury during video analysis of injurious events (Boden et al., 2009; Koga et al., 2010; Krosshaug et al., 2007). Compared to matched controls, injured athletes exhibit relatively similar mechanics at initial contact during the activity that led to injury. However, considering that ACL injuries are thought to occur around 40 msec after initial contact (Koga et al., 2010), the biomechanics during the time between initial contact and injury may be most important to identify risk factors for ACL injury. Compared to non-injured athletes, those that subsequently tore their ACL have exhibited significantly more knee abduction excursion in the 40-50 msec after initial contact (Boden et al., 2009; Koga et al., 2010; Krosshaug et al., 2007). Interestingly, the 40 msec preceding ACL rupture may be characterized by knee abduction coupled with knee internal rotation, with considerable amounts of knee external rotation occurring after injury (Koga et al., 2010). These findings may have implications for the risk factors associated with ACL injury, as increased external rotation range of motion typically thought of as a risk factor for injury may in fact be the subsequent movement that occurs as a result of ACL rupture. Whether knee abduction coupled with tibiofemoral internal or external rotation promotes higher risk of ACL injury is still unknown.

Despite the aforementioned evidence that supports knee abduction as a biomechanical risk factor for ACL injury, others have reported conflicting results (Goetschius et al., 2012; Smith et al., 2012). Goetschius et al. (2012) used data acquired from 2D video analysis (N= 20 injured, 45 non-injured, matched controls) during a modified DVJ to estimate peak knee abduction moment using a previously published algorithm (Myer, Ford, Khoury, Succop, & Hewett, 2011). Logistic regression analysis revealed no relationship between predicted knee abduction moment and ACL injury (Goetschius et al., 2012). Similarly, the Landing Error Scoring System (LESS), which assesses 2D kinematics (including knee abduction) during a modified DVJ, has also been reported to have no significant ability to predict ACL injury (Smith et al., 2012). Despite these conflicting findings, reducing dynamic knee valgus remains a primary goal of current ACL injury prevention programs.

Shallow Knee Flexion Angles. Landing with shallow knee flexion angles has also been implicated as a risk factor for ACL injury. Observational video analyses have reported that up to 90% of injured female athletes land with less than 30 degrees of knee flexion at initial contact and exhibit relatively low knee flexion excursions from initial contact to the estimated onset of ACL injury (Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). This is important because the ACL is subjected to the highest loads between 0-30 degrees of knee flexion, especially in the presence of a strong quadriceps contraction by creating high anterior tibial shear forces (Arms et al., 1984; Draganich & Vahey, 1990; Durselen et al., 1995; Markolf, Gorek, Kabo, & Shapiro, 1990; Renstrom et al., 1986). The risk associated with this landing strategy can be exacerbated if the athlete lands with their foot anterior to their center of mass, which may induce a large internal knee extension moment (Boden, Dean, Feagin, & Garrett, 2000; Boden et al., 2009). While observational analyses suggest that shallow knee flexion is present at the time of ACL injury, no prospective study has linked this movement strategy during a screening test to risk of subsequent injury.

Other. There are other movement strategies throughout the kinetic chain that may lead to heightened risk for ACL injury. Video analysis has revealed that during an injurious event, athletes land in less ankle plantarflexion, manifesting in initial contact with the heel or rearfoot, as opposed to the forefoot contact seen in controls (Boden et al., 2009). This may potentially cause the athlete's mass to be centered more over their heels than forefoot. More proximally, athletes land with less trunk flexion, and may exhibit greater levels of lateral trunk lean preceding injurious events, signifying that poor strength or control of proximal musculature may also have implications on ACL injury rates (Boden et al., 2009; Hewett, Torg, & Boden, 2009).

Summary. In summary, athletes that exhibit movement strategies consistent with lower extremity valgus and/or shallower knee and hip flexion angles may be at a higher risk of ACL injury during athletic competition. The risk of these movement strategies resulting in injurious events may be further exacerbated by landing flat-footed, or with an abnormal trunk position.

Basketball. As previously stated, prior research has suggested a number of biomechanical risk factors that may either be predictive of ACL injury or apparent at the time of ACL injury (Boden et al., 2009; Hewett et al., 2005; Koga et al., 2010; Krosshaug et al., 2007). Investigating these high-risk biomechanics during jumping and landing in women's basketball is important, considering the vertical nature of the game. Potentially high-risk movement strategies are especially evident in females when compared to males, which may factor into the gender discrepancy in ACL injury rates (Prodromos et al., 2007). Female high school basketball players have shown significantly greater levels of dynamic knee valgus, then their male counterparts (Ford, Myer, & Hewett, 2003). Specifically, male and female basketball players land (at initial contact) with similar knee abduction angles, yet females show considerably greater peak values and total knee abduction excursion during the descent phase than their male counterparts, especially when normalized to body height (Ford et al., 2003).

Another movement strategy that may have consequences on ACL injury rates is dynamic biomechanical asymmetry. Several studies have indicated that basketball athletes demonstrate side-to-side differences in knee abduction angles and GRF during landing activities (Bates, Ford, Myer, & Hewett, 2013a, 2013b; Cowley et al., 2006; Ford et al., 2003; Herrington, 2011). Increased knee abduction angles have been found in the dominant limb (preferred kicking limb), while increased GRF have been reported in the non-dominant leg (Cowley et al., 2006; Ford et al., 2003). This asymmetry may be exacerbated with repetitive landings, as larger dynamic biomechanical asymmetry in knee abduction angles and ground reaction forces have also been seen with consecutive jumps of the DVJ maneuver, with the second landing producing more asymmetry than the first (Bates et al., 2013a, 2013b). The high levels of dynamic biomechanical asymmetry found in women's basketball players may lead to the generation of abnormally high forces on one side and with a lateral center of mass displacement may further increase knee abduction or adduction loading. Further, these asymmetrical strategies may become habitual, leading to less reliance on one extremity and subsequent neuromuscular imbalances, which may result in that limb's reduced ability to overcome high intensity forces.

In summary, female basketball players can exhibit relatively high knee abduction angles and external moments during jump landings that may place them at high-risk for ACL injury. Further, asymmetrical biomechanics and muscle activation strategies during landing and cutting may place abnormally high forces on the knee. Improving these high-risk biomechanics and asymmetries should be an area of focus for ACL injury prevention programs in female basketball players.

Comparison to soccer. The aforementioned at-risk movement strategies in women's basketball players may be different than those exhibited by soccer players. This may help to explain the divergent efficacies of ACL injury prevention programs in these populations, as the high-risk biomechanics that need to be targeted may be different. To date, there are only two studies that have investigated the biomechanical differences between female basketball and soccer players during sport-specific activities (Cowley et al., 2006; A. Munro et al., 2012).

Two-dimensional video analysis has been used to quantify dynamic knee valgus through calculation of the frontal plane projection angle (FPPA). It is conventionally measured as the angle formed by a line representing the femur (anterior superior iliac spine to mid-patella) and tibia (mid-patella to mid-point of the ankle malleoli). Though the nature of 2D analysis takes into account both frontal and transverse plane motions, the FPPA has been reported to account for 58-64% of the variance in knee abduction angles calculated through 3D analysis (McLean et al., 2005). Munro et al. (2012) examined the FPPA at maximal descent during landing activities of 93 college-aged female athletes (52 soccer and 41 basketball players) who had specialized in their respective sports. Athletes performed both a bilateral drop jump landing and a single-leg landing for comparison. Statistical analysis revealed no significant differences in frontal plane measures during the bilateral landing task; however, statistically significant differences were found during the single-leg landing, whereas basketball athletes (mean frontal plane projection angle = 9.79±5.5°) showed larger measures of knee valgus than soccer players (mean frontal plane projection angle = 6.00±6.4°).

Similarly, Cowley et al. (2006) assessed 3D kinematics and kinetics during a DVJ landing in 15 single-sport high school basketball and 15 soccer players. Kinematically, there were no significant differences found between peak knee valgus angles or frontal plane measures at initial foot contact. However, basketball players showed a 10-15% greater peak vertical GRF ($p = .003$) and decreased stance time ($p < .001$) than soccer players. Larger magnitudes of vertical GRF and reduced stance duration during jumping activities may lead to higher levels of performance; however, a trade-off may exist, as a higher intensity of forces absorbed over a shorter period of time may leave basketball players at higher risk of injury during landing activities (Hewett et al., 2005). Further, because basketball players may land in greater angles of knee valgus (A. Munro et al., 2012), the combination of greater knee valgus motion and higher levels of GRF may biomechanically translate into higher knee abduction moments through a larger lever arm acting on the knee joint, contributing to a higher risk of ACL injury during landing activities.

Cowley et al. (2006) also compared the 3D kinematics and kinetics during a cutting maneuver in the same cohort of female soccer and basketball players. The cutting maneuver consisted of a forward jump with bilateral landing, followed by a 45° side-step cut in the direction of a visual, unanticipated cue. Results showed that, contrary to jump landings, soccer players exhibited 15% larger peak vertical GRF values ($p = .003$) and decreased stance time ($p < .001$) than basketball players during the cut, though no differences were seen in at-risk knee joint angles throughout the maneuver. While no performance variables were collected in this study, these characteristics signify that soccer players exhibit faster, more explosive cutting ability than basketball players, and basketball players exhibit faster, more explosive vertical jumping ability. It is debatable whether these characteristics lead to a higher or lower risk for injury, though the larger magnitudes of forces that occur during cutting may present more potentially injurious situations to soccer players.

In summary, these studies indicate that female basketball and soccer players show distinct movement strategies during jump landing and cutting activities. As expected according to their sport-specific demands, basketball players show characteristics that correlate with higher levels of jumping performance, while soccer players demonstrate more explosive cutting strategies. This may suggest that the high-risk movement strategies targeted by ACL injury prevention efforts may need to be designed to more effectively target sport-specific demands.

Need for Basketball-Specific ACL Injury Prevention Programs

In order to optimize injury prevention programs, Van Mechelen et al. (1992) proposed to establish the extent and the etiology/mechanism of injury. The preceding sections of this review have concluded that ACL injuries are common and concerning in women's basketball, with the predominant mechanism of injury as the result of a jump landing activity. The next step in the paradigm calls for the designing of interventions that effectively modify the risk factors associated with ACL injury in women's basketball players.

Previous studies indicate that established ACL neuromuscular injury prevention programs may effectively modify high-risk biomechanics by increasing knee flexion angles and reducing knee flexion and abduction moments during double-leg landings in the sagittal plane (Chappell & Limpisvasti, 2008; D. C. Herman et al., 2008; Hewett, Stroupe, Nance, & Noyes, 1996; Lephart et al., 2005; Lim et al., 2009; Padua & Distefano, 2009; Pollard et al., 2006). However, the specificity of training principle surmises that training is most effective when the training activities resemble the activity in which improvement is sought (Baechle & Earle, 2000). Because women's basketball is a multi-directional sport, most commonly requiring changes of direction vertically (jumping) and laterally (Ben Abdelkrim et al., 2007; Matthew & Delextrat, 2009; McInnes et al., 1995), injury prevention training may need to be focused on both double- and single-leg jump landings performed in the sagittal and frontal planes, in order to most effectively develop safer movement strategies.

To that end, current prevention strategies are significantly less successful in modifying high-risk biomechanics during single-leg landings (Brown et al., 2014). Brown et al. (2014) analyzed female athletes' lower extremity biomechanics during a sagittal plane single-leg landing before and after the completion of a standard neuromuscular or isolated plyometric or core stability/balance training program. No significant differences were reported in hip and knee sagittal and frontal plane biomechanics after any of the three training programs (Brown et al., 2014). Additionally, to date, there have been no reports of whether high-risk jump landing biomechanics are modified when performed in the frontal or transverse plane as a result of current prevention programs. Thus, current ACL injury prevention programs that focus primarily on double-leg sagittal plane movements may not provide the adequate stimulus to improve high-risk biomechanics during sport-specific non-sagittal plane and single-leg activities in this population.

Strictly modifying lower extremity biomechanics during double-leg sagittal plane activities may not impact the movement strategies employed during other sport-specific tasks. Evidence indicates that lower extremity biomechanics change when the same task is performed in various planes (Ford et al., 2006; Sinsurin et al., 2013a, 2013b). More specifically, single-leg landings in the frontal plane exhibit decreased levels of peak hip flexion and greater levels of peak knee abduction range of motion (Sinsurin et al., 2013a, 2013b), which suggests that frontal plane landings may pose greater injury risk than sagittal plane landings (Hewett et al., 2005). The direction (medial vs. lateral) of frontal plane landings also influences hip and knee biomechanics. Lateral landings result in greater levels of frontal plane hip range of motion excursion than medial landings, while medial landings require greater levels of frontal plane ankle excursion than lateral landings (Ford et al., 2006). Consequently, both the plane and direction of movement prior to landing can influence lower extremity biomechanics. Whether current ACL injury prevention programs lend protection to these motions has not been investigated, but may be a crucial component of future prevention efforts in women's basketball players.

Considering that movements in different planes elicit different high-risk biomechanics, traditional double-leg sagittal plane screening tests may be not be sensitive enough to provide a comprehensive assessment of high-risk movement strategies in women's basketball. Conventional injury risk screening batteries emphasize testing double-leg sagittal plane movements such as the drop vertical jump and tuck jump (Myer, Ford, & Hewett, 2008; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). Although single-leg and frontal plane tasks have been previously published (Ford et al., 2006), none have been adopted into screening batteries as part of common/best practice. Because evidence suggests that different planes of movement elicit different lower extremity biomechanics (Sinsurin et al., 2013a, 2013b), and that high-risk sports involve numerous non-sagittal plane demands, the screening paradigm for multi-directional sport athletes may need to be modified to account for the specific demands of their sport. In women's basketball, these tasks likely need to include single-leg landings, and jump landings in the frontal plane.

Therefore, in an effort to better understand why ACL injury prevention programs have not been successful in women's basketball players, future research is necessary to:

1) characterize and compare the high-risk movement strategies of women's basketball players during double- and single-leg sagittal and non-sagittal plane jump landings to determine if conventional screening tests provide a comprehensive analysis of high-risk lower extremity biomechanics

2) analyze the extent of change of lower extremity biomechanics during these tasks after completing a prevention program to determine whether current ACL injury prevention programs alter biomechanics during sport-specific tasks, and

3) determine whether these changes occur to the same extent in women's basketball and soccer players so as to elucidate whether sport-specific demands or physical characteristics associated with a specific sport influence an athlete's response to an ACL injury prevention program.

Conclusion

Despite equally concerning ACL injury rates in women's basketball and soccer, considerably more injury prevention research has been performed on soccer players. This has led to ACL injury prevention programs exhibiting a significant reduction of ACL injuries in women's soccer, yet with less success in women's basketball (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007). This may be because ACL prevention programs have been designed for women's soccer, and subsequently implemented in women's basketball without modification or consideration of the differences between the two sports. The mechanism of injury in these two sports is very different, as basketball players incur ACL injuries more often during jump landing activities (often on a single leg) than soccer players (Piasecki et al., 2003). Additionally, physical characteristics and movement strategies (during similar landing and cutting tasks) may differ between sports. Based on their collective differences in sport-specific demands, injury situations, physical characteristics and movement strategies, the same prevention program may not be appropriate for both women's basketball and soccer players.

Based on the observed differences in these sports previously described, research is needed to elucidate why ACL injury prevention programs are less successful in women's basketball players. Past research has shown that after completing a prevention program, both women's basketball and soccer players display improved strength, power and high-risk landing biomechanics during sagittal plane tasks (Lim et al., 2009; Noyes et al., 2012; Noyes et al., 2013); however, no prior studies have compared the magnitude of training response between the two groups to see if the programs' effect is greater in one group than the other. Additionally, no studies have examined changes in landing biomechanics during non-sagittal plane tasks. Considering the higher prevalence of these activities in women's basketball compared to women's soccer, understanding the effects of an ACL injury prevention program on changing high-risk biomechanics during non-sagittal plane and single-leg landing tasks may be crucial to the success of prevention programs in basketball. In order to move forward with the design and implementation of equally effective interventions for women's basketball players, research is needed to understand the differential effects of current ACL injury prevention programs on high-risk biomechanics during single-leg, sagittal and non-sagittal plane tasks in both sports.

CHAPTER III

METHODS

Objective

The primary objective of this study was to determine the degree to which women's basketball and soccer players respond differently to an established ACL injury prevention program, as measured by improvements in multi-planar lower extremity biomechanics during sagittal and non-sagittal plane jump landing tasks. The approach was to recruit women's basketball and soccer players, then measure their jump landing biomechanics during double- and single-leg sagittal and frontal plane jump landing tasks before and after the completion of an established 6-week ACL injury prevention program (LaBella et al., 2011). The central hypothesis was that women's basketball and soccer players would respond similarly to the ACL injury prevention program, but that the ACL injury prevention program would provide a greater stimulus to improve hip and knee biomechanics (hip flexion, adduction and internal rotation, and knee flexion, abduction and internal/external rotation) during sagittal plane jump landing tasks, than during non-sagittal plane or single-leg jump landing tasks.

Participants

Ninety-nine high school-aged female athletes (44 basketball, 55 soccer) were recruited from three local clubs to participate in the study. In order to be included in the study, participants had to be cleared for unrestricted activity and reported no current lower extremity injury. Potential participants were excluded if they reported: 1) lower extremity injury or surgery in the six months prior to the study, 2) vestibular or balance disorders that could cause participants to lose balance during jumping activities, or 3) cardiovascular disease. Each participant's parent/guardian read and signed a parental consent form, while participants read and signed a child assent form. Both forms were approved by the Institutional Review Boards of the University of North Carolina at Greensboro and High Point University (Appendix A). Upon entry into the study, athletes were cluster randomized by team in to one of four groups: (1) basketball intervention group, (2) basketball control group, (3) soccer intervention group, and (4) soccer control group. Participants that were unable to commit to a 6-week intervention were excluded from the analyses for Hypothesis 2 and 3, but included for Hypothesis 1.

Procedures

Each participant attended a pre- and post-test data collection session. Testing sessions for the intervention groups were held within two weeks prior to initiation of the intervention program and 2-10 days after completion of the intervention. Participants in the control groups completed the pre- and post-test approximately 8 weeks apart at the same general time of season as the intervention groups. Participants were instructed to wear compression shorts to minimize pelvic marker movement during biomechanical analysis and donned standardized, laboratory-provided footwear (adidas® adipure Trainer

360, Beaverton, OR) to control for the effect of footwear on biomechanical landing patterns.

Demographics and Injury, Physical Activity and Sport History

At the pre-test participants filled out an electronic form (REDCap^{TM} software, Version 4.14) assessing age, sex, shoe size, year in school, past medical history, sport participation history, physical activity history, injury history, and menstrual history (Appendix B). At the post-test, participants completed another electronic form again assessing physical, injury and menstrual history since the pre-test.

Anatomical Measurements

Height (cm) and mass (kg) were recorded using a medical-grade scale and stadiometer (Seca, Hamburg, Germany) and BMI was calculated at each testing session. Participants' sagittal plane knee laxity and arch height index were measured for use in future analyses. Raw data of these tests can be found in Appendix C. Anterior and posterior knee laxity were assessed with the KT-2000^{TM} Knee Arthrometer (MEDmetric Corportation, San Diego, CA). Anterior knee laxity was defined as the amount of anterior tibial displacement at 133 N of anteriorly-directed force and posterior knee laxity as the amount of posterior tibial displacement at 90 N of posteriorly-directed force. Participants were placed in the supine position for testing with a bolster supporting the distal femur, the knee in 25 degrees of knee flexion and bilateral feet in a foot cradle, per the manufacturer's directions. A Velcro strap was placed around the subjects' thigh to prevent any hip rotation. Three repetitions of cyclic anterior to posterior and posterior to anterior directed forces were applied to the anterior and posterior aspect of the tibia, respectively, with the last two repetitions averaged for analysis. The primary investigator established good test-retest reliability ($ICC_{2,3}$ = 0.82) and precision (SEM = 0.8 mm) prior to data collection.

The Arch Height Index Measurement System (JAK Tool and Model, LLC, Cranbury, NJ) was used to measure arch height index in concordance with established techniques (R. J. Butler, Hillstrom, Song, Richards, & Davis, 2008). Arch height index was taken in sitting and standing to measure the change in arch structure between non- and full- weight bearing. While measuring sitting arch height index, the participant was positioned with 90 degrees of hip and knee flexion and feet resting on the floor. The participants' heel was placed firmly against the heel cup and a horizontal sliding caliper was placed firmly against the end of the longest toe to measure total foot length. A second horizontal sliding caliper was positioned at the medial aspect of the first metatarsophalangeal joint. The distance between the posterior aspect of the heel and the first metatarsophalangeal joint was measured as the truncated foot length. The final horizontal sliding caliper was positioned at a distance equal to one-half of the total foot length and an attached vertical sliding caliper was gently placed on the dorsum of the foot. The vertical distance from the floor to the dorsum of the foot was measured as the dorsum height. The arch height index was calculated as the ratio of dorsum height to truncated foot length. The standing arch height index was measured in similar fashion, except the subject was standing in a relaxed stance with equal weight on each leg. The primary investigator established excellent test-retest reliability ($ICC_{2,3}$ = 0.96) and precision (SEM = 0.005 cm) prior to data collection.

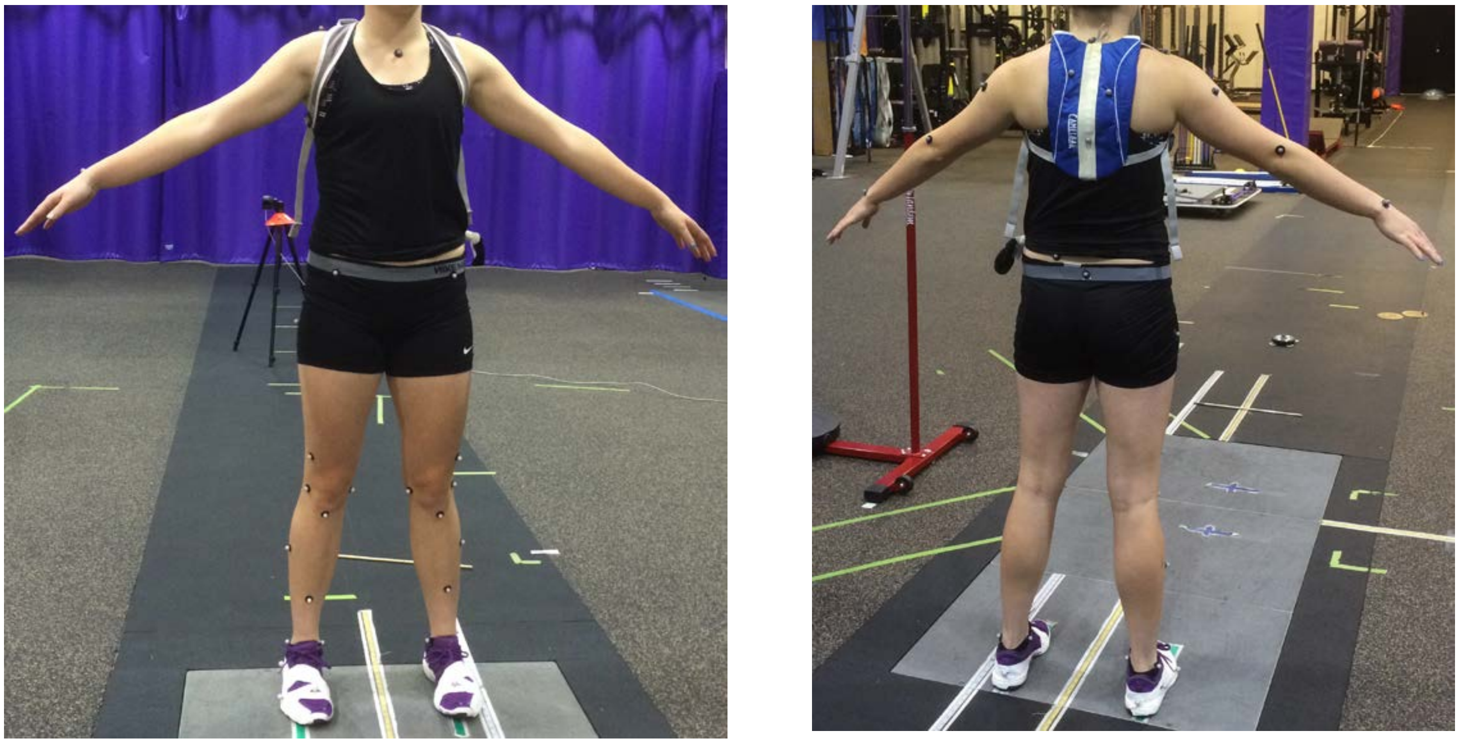
Limb Dominance

The definition of limb dominance may vary between sports (Theoharopoulos & Tsitskaris, 2000), especially considering the different sport-specific demands associated with basketball and soccer. Therefore, limb dominance was defined as the most powerful leg as measured by the triple-hop for distance test. The triple-hop for distance test was performed with a standard cloth tape measure fixed to the ground, perpendicular to the starting line (Hamilton, Shultz, Schmitz, & Perrin, 2008). The limb that was tested first was counterbalanced between participants and remained the same for the pre- and post-test. Instructions were given to perform three consecutive maximal hops forward on the same limb without stopping. One to three practice trials were given (self-selected) on each leg, and the next three subsequent test trials were recorded. Measurements were taken from the starting line to the point of toe contact upon completing the third hop. Trials were repeated if the participant lost balance or contacted the ground with their opposing leg at any instance throughout the test. Three trials on each leg were recorded and the limb that elicited the largest horizontal distance was subsequently defined as the dominant limb.

Biomechanical Measurements

Instrumentation. Each subject was instrumented for three-dimensional biomechanical analysis with 43 reflective markers placed on the sternum, sacrum, left PSIS, C7, three points on the upper back (via a thin backpack), and bilaterally on the shoulder, upper arm, elbow, wrist, ASIS, greater trochanter, mid-thigh, medial and lateral knee joint line, tibial tubercle, mid-shank, distal shank, medial and lateral malleolus, and to the foot at the heel, posterior lateral foot, anterior lateral foot and toe via double-sided tape (Figure 3.1). A static trial was collected to determine each subject's neutral alignment and anatomically define each body segment, by which subsequent biomechanical measures were referenced. Three-dimensional motion data were collected with Cortex software (version 5, Motion Analysis Corporation, Santa Rosa, CA, USA) using a 14-camera system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA, USA) that sampled at 200 Hz. Kinetic data was sampled at 1200 Hz, collected by dual, in-ground, multi-axis force plates (AMTI, Watertown, MA, USA), such that each force plate collected data from a single leg.

Figure 3.1. Participant Instrumented for Three-dimensional Motion Capture with 43 Retroreflective Markers on her Trunk, Upper and Lower Extremities.



Functional Movement Tasks. Participants completed five different jump landing tasks: 1) drop vertical jump (DVJ), 2) double-leg forward jump in the sagittal plane (SAG-DL), 3) single-leg forward hop in the sagittal plane (SAG-SL) on each limb, 4) double-leg lateral jump in the frontal plane (FRONT-DL) and 5) single-leg lateral hop in the frontal plane (FRONT-SL) on each limb. The performance consistency for each task was assessed prior to the onset of this study, with all tasks exhibiting good to excellent consistency and precision (Table 3.1). The order of all jump landing tasks was randomized for each participant prior to the start of the study, yet performed in identical order at the pre- and post-test sessions. For each task, the participant performed 1-3 practice trials or until they felt comfortable with the task and the investigator deemed the performance adequate. After practice trials were completed, each task was performed three times at maximal intensity while lower extremity biomechanics were recorded.

Table 3.1. The Performance Consistency Results of the Five Jump Landing Tasks Utilized in this Study. Reported are $ICC_{2,k}$ (SEM) of peak angles and peak external moments of tests performed by the same athlete (n=15) two to five days apart (J. B. Taylor, Ford, Nguyen, & Shultz, 2016).

	DVJ	SAG-DL	SAG-SL	FRONT-DL	FRONT-SL
Peak Angle					
Hip Flexion	0.77 (4.5°)	0.86 (3.1°)	0.86 (3.4°)	0.71 (4.1°)	0.84 (3.2°)
Hip Adduction	0.92 (1.2°)	0.87 (1.8°)	0.87 (2.0°)	0.89 (2.5°)	0.79 (3.5°)
Hip Internal Rotation	0.78 (2.6°)	0.86 (2.9°)	0.63 (3.5°)	0.94 (1.9°)	0.84 (3.2°)
Knee Flexion	0.91 (2.9°)	0.87 (2.1°)	0.95 (1.4°)	0.94 (1.6°)	0.90 (2.0°)
Knee Abduction	0.82 (2.6°)	0.87 (1.8°)	0.90 (1.7°)	0.81 (3.0°)	0.84 (2.0°)
Knee Internal Rotation	0.92 (1.5°)	0.95 (1.7°)	0.90 (2.0°)	0.80 (2.2°)	0.89 (1.6°)
Knee External Rotation	0.85 (2.3°)	0.85 (1.9°)	0.85 (1.9°)	0.89 (2.0°)	0.84 (2.3°)
Peak External Moment					
Hip Flexion	0.87 (8.8 Nm)	0.74 (10.5 Nm)	0.82 (29.8 Nm)	0.88 (9.6 Nm)	0.84 (13.3 Nm)
Hip Adduction	0.80 (4.6 Nm)	0.80 (3.9 Nm)	0.94 (7.7 Nm)	0.92 (4.6 Nm)	0.88 (8.8 Nm)
Hip Internal Rotation	0.80 (4.2 Nm)	0.80 (5.3 Nm)	0.82 (7.1 Nm)	0.80 (6.3 Nm)	0.70 (9.2 Nm)
Knee Flexion	0.77 (10.8 Nm)	0.91 (5.9 Nm)	0.91 (7.5 Nm)	0.91 (7.3 Nm)	0.90 (8.5 Nm)
Knee Abduction	0.91 (3.4 Nm)	0.88 (3.4 Nm)	0.85 (4.3 Nm)	0.78 (5.0 Nm)	0.93 (5.1 Nm)
Knee Internal Rotation	0.79 (2.6 Nm)	0.90 (2.0 Nm)	0.63 (2.7 Nm)	0.87 (2.0 Nm)	0.97 (2.0 Nm)
Knee External Rotation	0.67 (2.3 Nm)	0.93 (1.4 Nm)	0.97 (1.7 Nm)	0.92 (2.8 Nm)	0.87 (3.7 Nm)

Prior to performing the jump landing tasks, an overhead target was set to the participant's maximal reach during a countermovement jump. An overhead target was included for all jumping tasks because it has been reported to promote higher intensities and forces when performing a maximal vertical jump (Ford et al., 2005). Each participant performed 3-5 maximal countermovement jumps by starting with one foot on each force plate and performing a squat followed by a maximal vertical jump. A ball was suspended above the force plates to serve as a target during all tasks. Participants were instructed to jump as high as possible, attempting to reach towards the ball and tap with both hands. The target was adjusted and set to the participants' maximal countermovement jump reach, such that the participants were able to barely touch the ball with both hands upon reach. The target was maintained at the same height and location for all subsequent jumping tasks. A pilot study established that this methodology elicited consistent performance during all tasks (Table 3.1).

The DVJ was performed as previously reported (J. B. Taylor et al., 2016). A 31-cm box was placed directly adjacent to the force plates. Participants were instructed to stand with their feet 35-cm apart and their toes hanging off of the front edge of the box. When ready, participants slid forward off the box with both feet at the same time, landed simultaneously with both feet and immediately performed a maximal countermovement jump while reaching for the target with both hands. The SAG-DL task was a standard forward jump with subsequent maximal countermovement jump. The participant was positioned a distance equal to their leg length from the edge of the force plates. Leg length was measured as the distance from the most superior palpable aspect of the greater trochanter to the most inferior aspect of the lateral malleolus using a standard cloth tape measure. Subjects were then instructed to jump forward, aiming to land with their feet in the center of each force plate at the same time and immediately perform a maximal countermovement jump, reaching up for the target with both hands. Similar methods were used for the single-leg sagittal plane hop (SAG-SL), though the subject was positioned a distance equal to one-half of their leg length away from their force plates and were asked to hop off a single-leg, land on the same leg and immediately perform a maximal countermovement hop, attempting to reach the target with the contralateral hand. The contralateral upper extremity was used as the reaching arm during both single-leg landings because it most resembled athletic movements of multi-directional jumping sports. The SAG-SL task was performed three times on each leg.

The FRONT-DL task was a lateral jump with double-leg landing and immediate maximal countermovement jump. The subject was positioned such that they were straddling a line placed a distance equal to one-half of their leg length away from the lateral edge of the nearest force plate. The subject was then instructed to keep their trunk facing forward and jump laterally such that each foot landed on a separate force plate at the same time and immediately perform a maximal countermovement jump, reaching for the target with both hands. Similar techniques were used for the FRONT-SL task. Subjects were again placed at a distance equal to one-half of their leg length away from the closest force plate, standing on their outside leg. The subject was instructed to hop sideways to the middle of the second force plate (located 36 cm plus one-half of leg length away), land on the opposite limb, and immediately perform a maximal countermovement hop, reaching toward the target with the hand contralateral to the landing limb. Subjects performed the FRONT-DL and FRONT-SL three times in both directions.

Data reduction. Biomechanical data were processed in Visual3D (Version 5, C-Motion, Inc., Rockville, MD, USA) with custom MATLAB (Version 8.0, The Mathworks, Natick, MA) code. Hip joint centers were calculated using the Bell method (Bell, Pedersen, & Brand, 1990), and the knee and ankle joint centers were calculated as the centroid position of the medial and lateral femoral epicondyles and malleoli, respectively. Joint angle and moment data were subjected to a low-pass fourth-order Butterworth filter with a cutoff frequency of 12 Hz. A Euler rotational sequence of flexion/extension, abduction/adduction, and internal/external rotation was used to process joint angle data. Hip flexion, adduction, and internal rotation and knee extension, adduction, and internal rotation were reduced as positive motions.

Kinematic variables of interest were peak angles and excursion values for hip flexion, adduction and internal rotation, and knee flexion, abduction, internal rotation and external rotation. Joint excursions were calculated by subtracting the angle at initial contact (first point that GRF surpasses 10N) from the peak angle during the landing phase (initial contact to maximal descent of the center of gravity). Kinetic variables included peak hip flexion, adduction and internal rotation, and knee flexion, abduction, internal rotation and external rotation external moments during the landing phase. All moments were normalized by the subjects' height (m) and mass (kg) to allow for more accurate comparisons between groups of athletes. These variables were selected based on collective thought that they may either influence dynamic valgus collapse or promote stiff-leg landings, theorized as the predominant mechanisms of ACL injury in female athletes (Hashemi et al., 2011; Quatman & Hewett, 2009; Schmitz et al., 2009). Means of all successful trials for each task were calculated and used in statistical analyses.

Performance measures. In addition to the measurement of biomechanical changes after performing the ACL injury prevention program, identifying changes in physical performance may help entice coaches and athletes to be more compliant with the training program; therefore, in addition to the triple hop for distance test, an agility test was performed at the pre- and post-testing sessions for future analysis (Appendix C). Agility was measured using a FITLIGHT Trainer™ (FITLIGHT Sports Corp., Ontario, Canada) timing system during the Agility T-Test (A. G. Munro & Herrington, 2011). The Agility T-Test was chosen because it arguably most closely resembles the sport-specific demands of both basketball and soccer, encompassing sprinting, side-shuffling, and backwards running. Participants started by looking straight ahead with their behind a start/finish line where one FITLIGHT was placed on a stand at knee level. The examiner counted down from 3 and at 1 initiated the FITLIGHT system. Participants were instructed to start as soon as they either saw the FITLIGHT at the starting line illuminate or heard the timing gate make a beeping noise. Participants then sprinted forward for 10m, and touched a second illuminated FITLIGHT that was laid flat on the ground. Participants then alternated side-shuffling to the right or left, as determined by the investigator prior to the start of the trial. Upon side shuffling 5m in one direction, participants again touched a FITLIGHT flat on the ground and immediately changed direction to side shuffle 10m in the opposite direction, touched a FITLIGHT, and again 5m back to the middle FITLIGHT. Upon touching the last light, participants then sprinted backwards at maximal speed through the finish line. Time was measured as the total time between crossing the start and finish line. Four total trials were performed, with two trials side-shuffling to the right first, and two to the left first. The order of trials was counterbalanced between participants.

ACL Injury Prevention Program

The ACL injury prevention program developed by Labella et al (2011) was used in this study. The program encompasses strength, agility, balance and plyometric jump training and was deemed the best program to test the aforementioned hypotheses because (1) it was the most current reported ACL injury prevention program used in women's basketball, (2) it was the most realistic and least obtrusive for implementation, based on coaches desires to limit the amount of practice time missed, and (3) it strongly emphasized sagittal plane movements. The injury prevention program lasted 20-25 minutes in duration and was implemented at the beginning of each scheduled practice session over a 6-week period, serving as the team's warm-up routine. Six weeks was chosen because it best aligned with teams' offseason schedules and was consistent with the duration of training used in other ACL injury prevention studies (Myklebust et al., 2003; Olsen et al., 2005). Additionally, past evidence supports the ability to observe neuromuscular adaptations within six weeks of the onset of training (Chappell & Limpisvasti, 2008; Chimera, Swanik, Swanik, & Straub, 2004; Dawson & Herrington, 2015; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009; Myer, Ford, Palumbo, & Hewett, 2005). The same member of the research team was present at all intervention sessions to help administer the program and provide verbal biomechanical feedback to the athletes. Attendance was taken at each intervention session for compliance calculations. Additionally, all participants that missed a training session were asked to give a reason for missing in order to track time lost from injury, vacation, non-compliance, or other reasons.

The exact progression of exercises performed throughout the program is found in Table 3.2. In accordance with the injury prevention program published in the original manuscript, athletes were given real-time feedback with verbal cues such as “land softly” and “don’t let your knees cave inward” during all exercise sessions to focus on limiting lower extremity valgus and promoting greater levels of knee and hip flexion (LaBella et al., 2011). Members of the control group were instructed to continue with normal basketball and soccer tactical/skill training, refraining from participation in any dedicated injury prevention, strength, or plyometric training programs.

Table 3.2. Training Program Used in this Study (Originally Developed by LaBella et al, 2011)

WEEK 1	WEEK 2	WEEK 3-6
Jog	Jog	Jog
Dynamic Warm-Up*	Dynamic Warm-Up*	Dynamic Warm-Up*
Strengthening		
Heel Raises†	Heel Raises†	Heel Raises†
Squats†	Squats†	Squats†
Plank/Side Plank‡	Plank/Side Plank‡	Plank/Side Plank‡
Push-ups†	Push-ups†	Push-ups†
Forward Lunge†	Lateral Lunge†	Lateral Lunge†
Supermans†	Diagonal Lunge†	Diagonal Lunge†
Swimmers†	Supermans†	Walking Lunge†
	Swimmers†	Supermans†
	Modified Supermans†	Swimmers†
		Modified Supermans†
Plyometrics		
Ankle Bounces‡	Ankle Bounces‡	Ankle Bounces‡
Tuck Jumps‡	Tuck Jumps‡	Tuck Jumps‡
180 degree rotate‡	Squat Jumps‡	Squat Jumps‡
Squat Jump‡	Forward/Lateral Cone Jumps‡	Forward/Lateral Cone Jumps‡
DL Broad Jump for Distance^	Scissor Jumps‡	SL Hop, Hop, Stick^
Forward/Lateral Cone Jumps‡	Lateral Bounding‡	SL Jump for Distance^
SL Bound in Place^	SL Hop, Hop, Stick^	Jump into Bounding‡
	Broad Jump x3, Vertical Jump^	Diagonal Bounding‡
Agility		
Shuttle Run∞	Shuttle Run∞	Shuttle Run∞
Diagonal Run∞	Diagonal Run∞	Diagonal Run∞
Lateral Shuffle∫	Lateral Shuffle∫	Lateral Shuffle∫

*dynamic warm-up included 50ft each of: jogging, skipping, carioca, side shuffle with arm swing, sprint at 75% maximum, high-knee skipping, high-knee carioca, sprint at 100% maximum, backward jog, bear crawl, butt kickers, backward jog half-length, turn and sprint, and diagonal skipping. Also 10 repetitions each of arm swings, trunk rotations, and leg swings

† activities performed for desired number of repetitions: week 1- 10 reps, week 2- 20 reps, week 3-6- 30 reps

‡ activities performed for desired amount of time: week 1- 10 seconds or reps, week 2- 20 seconds or reps, week 3-6- 30 seconds or reps

^ activities performed 5 times for double-leg (DL) and 5 times on each side for single-leg (SL) tasks

∞ agility exercises performed for 50 feet, 10 repetitions

∫ agility exercises performed for 15 feet, 10 repetitions

Statistical Plan

All statistical analyses were performed in SPSS, version 23 (IBM Corp, Armonk, New York), using measures from the dominant leg, with statistical significance set a priori at α=.05 for all analyses. The following statistical plan was used for each hypothesis.

Hypothesis 1 stated: *Prior to training, women's basketball athletes will exhibit no significant differences in high-risk hip (flexion, adduction, internal rotation) and knee (flexion, abduction, internal and external rotation) kinematics, but will generate greater hip (flexion, adduction, internal rotation) and knee (flexion, abduction, internal and external rotation) external joint moments during jump landing activities than women's soccer players.* To test this hypothesis, biomechanical data from each task performed during the pre-test were included. Athletes (n=10) who had participated in both basketball and soccer during the previous academic year were excluded for this analysis to better isolate sport-specific training effects. All other participants, regardless of group (control and intervention) membership, were included in the analysis because pre-test scores were immune to intervention effects. MANOVAs were performed to test for differences in dominant leg lower extremity biomechanical variables between basketball and soccer players. Three separate MANOVAs were performed for each of the five tasks, such that each one included seven different, yet related biomechanical variables 1) hip and knee peak angles, 2) hip and knee angular excursions, and 3) hip and knee joint moments. Multivariate statistical significance for the sport main effect were analyzed using Wilk's Lambda for each model. Statistically significant main effects signified that there were biomechanical differences between women's basketball and soccer athletes, which allowed for post-hoc pairwise comparison of the variables using independent t-tests.

Prior to testing Hypothesis 2 and 3, 2 (sport) x 2 (training group) MANOVAs with planned post-hoc pairwise comparisons were performed to assess any baseline biomechanical differences between intervention and control groups. Six separate MANOVAs were performed for each jump landing task, such that peak kinetic, peak kinematic and excursion measurements of each motion were included for 1) hip flexion, 2) hip adduction, 3) hip internal rotation, 4) knee flexion, 5) knee abduction, and 6) knee internal and external rotation were included in each model. The training group main effect was analyzed using Wilk's Lambda to identify differences in baseline lower extremity biomechanics between control and intervention groups. Statistically significant main effects were followed with pairwise comparisons using independent t-tests. Then, the training group x sport interaction was analyzed using Wilk's Lambda. Statistically significant interactions were followed with planned pairwise comparisons (basketball intervention vs. control group, and soccer intervention vs. control group) using independent t-tests. Statistically significant differences between groups were later controlled for during subsequent statistical analyses.

Hypothesis 2 and 3 were related to the repeated measures experimental design, and were analyzed using an intention-to-treat principle and a last observation carried forward model (A. Herman, Botser, Tenenbaum, & Chechick, 2009; Portney & Watkins, 2009). Specifically, Hypothesis 2 stated: *After 6 weeks of training, high-risk* *biomechanics will improve to a larger extent during sagittal plane than frontal plane jump landing tasks.* To test this hypothesis, delta scores were computed (post-test minus pre-test value) for all biomechanical variables during the SAG-DL, SAG-SL, FRONT-DL and FRONT-SL (leading with the dominant leg) tasks. Delta scores were entered in to 2 (training group) x 4 (task) repeated measures MANOVA models. Similar to the analyses used to assess differences at baseline, six separate analyses were performed for each selected motion (hip flexion, adduction, hip internal rotation, knee flexion, abduction, knee internal and external rotation) such that the peak kinetic, peak kinematic and excursion measurements of all tasks were included as dependent variables in the same model (e.g. peak hip adduction moment, peak hip adduction angle, and frontal plane hip excursion). Multivariate statistical significance was analyzed for the group main effect and group x task interaction using Wilk's Lambda. Follow-up post-hoc pairwise comparison using independent t-tests were performed to identify significant group main effects. Significant group x task interactions were followed with planned independent t-tests between intervention and control group for each task, and paired t-tests of delta scores comparing the intervention group's delta scores of SAG-DL task to delta scores of the other three tasks. Cohen's *d* effect sizes and 95% confidence intervals (CI) were calculated for all biomechanical variables that exhibited statistically significant effects.

Hypothesis 3 stated: *After 6 weeks of training, there will be no significant differences in biomechanical changes in women's basketball compared to women's soccer players.* To account for sport-specific biomechanical profiles, while identifying sport-specific responses to the training program, 2 (group) x 2 (sport) MANCOVA models of post-test scores were performed while covarying for pre-test scores (Rausch, Maxwell, & Kelley, 2003). For each jump landing task, six separate MANCOVA models were established, such that all biomechanical variables (peak angle, excursion, peak joint moment) were again associated with each joint motion. The sport x group interaction was analyzed using Wilk's Lambda, and statistically significant interactions were followed with planned post-hoc comparisons using univariate ANCOVAs. Specifically, while controlling for pre-test scores, post-test scores of the following cohorts were compared 1) basketball intervention and control group, 2) soccer intervention and control group, and 3) basketball and soccer intervention groups. Effect sizes (ES), in the form of partial eta-squared values were calculated for all biomechanical variables that exhibited statistically significant effects.

Additionally, independent t-tests were performed to identify whether one sport attended more training sessions than the other. Any differences were controlled for in follow up ANCOVA models for all significant interactions between the intervention groups by controlling for both pre-test values and number of training sessions attended to analyze whether any identified sport-specific responses were due to more than the volume of training.

Power Analysis

A power analysis was performed to compute the required effect size given a total of 80 participants (20 players per group) and 80% power at a statistical significance criterion of 0.05 using G*Power, version 3.1.2. Results indicated that an effect size of 0.38 was needed in order for statistical significance to be reached. This effect size was comparable to previous studies that reported biomechanical changes after completion of an ACL injury prevention program (Table 3.3) (Chappell & Limpisvasti, 2008; D. C. Herman et al., 2008; Lephart et al., 2005; Lim et al., 2009; Pollard et al., 2006). Thus, a minimum sample size of 80 was deemed adequate and appropriate.

Table 3.3. Average Effect Sizes of the Change in Knee Biomechanics After Completion of Various ACL Injury Prevention Programs.

Measure	Study	Task	Effect Size
Knee flexion angle (peak)	Chappell (2008)	DVJ	0.53
	Pollard (2006)	DVJ	0.26
	Herman (2008)	DVJ	0.46
	Hewett (1996)	VJ	0.17
	Lim (2009)	VJ	0.41
	Lephart (2005)	VJ	1.06
Knee flexion moment (peak)	Chappell (2008)	DVJ	0.42
	Lim (2009)	VJ	1.74
	Lephart (2005)	VJ	0.45
Knee abduction angle (peak)	Pollard (2006)	DVJ	0.41
	Lephart (2005)	VJ	0.12
Knee abduction moment (peak)	Lim (2009)	VJ	0.75
	Lephart (2005)	VJ	0.93

DVJ: Drop Vertical Jump; VJ: Vertical Jump

CHAPTER IV

MANUSCRIPT I

Title

Biomechanical differences in female basketball and soccer players during single- and double-leg multi-directional jump landings.

Abstract

Context

Anterior cruciate ligament injury prevention programs are less successful in basketball than soccer and may be due to distinct movement strategies that these athletes develop from sport-specific training.

Objective

To identify biomechanical differences between female basketball and soccer players during multi-directional jump landings. We hypothesized that basketball players would exhibit higher forces and measures of dynamic knee valgus (hip adduction, internal rotation, knee abduction, external rotation) than soccer players.

Design

Cross-sectional.

Setting

Research laboratory.

Patients or Other Participants

Eighty-nine female athletes who played competitive basketball (n=40) or soccer (n=49) at the middle- or high-school level.

Intervention(s)

Three-dimensional biomechanical analysis was performed during a drop vertical jump (DVJ), double- (SAG-DL) and single-leg forward jump (SAG-SL), and double- (FRONT-DL) and single-leg (FRONT-SL) lateral jump.

Main Outcomes Measures

Peak angles, excursions, external joint moments, and joint energetics of the hip and knee were analyzed for sport differences using MANOVA models ($p<.05$).

Results

Basketball players landed with less hip and/or knee excursion during all tasks ($p<.05$) except for the SAG-SL task, where basketball players landed with greater peak hip flexion angles ($p=.04$). The FRONT-SL task elicited the most distinct sport-specific differences, including decreased hip adduction ($p<.001$) angles, increased hip internal rotation ($p=.003$), and increased relative knee external rotation ($p=.001$) excursions in basketball players. Additionally, the FRONT-SL task elicited greater forces in knee abduction (*p*=.003) and lesser forces in hip adduction (*p*=.001) and knee external rotation (*p*<.001) in basketball players. Joint energetics were different during the FRONT-DL task, as basketball players exhibited less sagittal plane energy absorption at the hip (*p*<.001), and greater hip (*p*<.001) and knee (*p*=.001) joint stiffness.

Conclusions

Sport-specific movement strategies were identified during all jump landing tasks, such that soccer players exhibited a more protective landing strategy than basketball players.

Key Words

sport-specific, multi-directional, biomechanics, ACL, frontal plane

Introduction

Of women's high school team sports, basketball and soccer have the highest rates of general lower extremity and anterior cruciate ligament (ACL) injuries (Barber Foss, Myer, & Hewett, 2014; Gornitzky et al., 2015; Hootman et al., 2007). Although both sports possess relatively high risks of injury, women's basketball players suffer higher rates of ACL tears from a non-contact mechanism than women's soccer players (Agel et al., 2005), and are more likely to suffer severe concomitant injuries (Granan et al., 2013). While this suggests a critical need for ACL injury prevention programs in women's basketball players, these programs are more commonly administered and reported to be substantially more successful in women's soccer populations (Michaelidis & Koumantakis, 2013; O'Brien & Finch, 2014; Prodromos et al., 2007). Because current ACL injury prevention programs are administered as "one size fits all" training regimens, the differential success of these programs in soccer versus basketball may in part be attributable to sport-specific differences in ACL injury mechanisms. Specifically, while basketball players predominantly tear their ACL during jumping and landing, soccer players are typically injured during cutting maneuvers (Faude et al., 2005; Piasecki et al., 2003). Thus, fundamental differences in sport-specific movement patterns may be an important consideration in further refining injury risk and prevention strategies.

Research has shown that an athlete's biomechanical movement strategy can be effectively modified with neuromuscular preventive training (Hewett et al., 1996; Lephart et al., 2005). To that end, understanding differences in biomechanical strategies between women's basketball and soccer players may assist sports medicine researchers and clinicians to better target sport-specific high-risk motions and design more effective prevention programs for women's basketball. To date, limited research has compared movement strategies between these sports. Of these few studies, basketball players are reported to perform jump landings with higher vertical ground reaction forces over a shorter timeframe than soccer players, while soccer players exhibit higher forces during cutting maneuvers (Cowley et al., 2006). These differences are important, considering athletes that suffer ACL injuries land with 20% higher ground reaction forces than non-injured athletes (Hewett et al., 2005). Additionally, basketball players have been reported to exhibit greater levels of lower extremity valgus during single-leg landings than soccer players (A. Munro et al., 2012), which has also been prospectively identified to be significantly larger in athletes that subsequently tear their ACL (Hewett et al., 2005).

While these studies indicate women's basketball players exhibit higher-risk movement strategies than soccer players during some athletic tasks, these comparisons have been limited to analyses of jump landing activities performed predominantly in the sagittal plane, using tasks such as drop vertical jumps (DVJ) and single-leg drop landings (Cowley et al., 2006; A. Munro et al., 2012). Previous research indicates that lower extremity biomechanics change as the movement plane and direction of movement change (Ford et al., 2006; Sinsurin et al., 2013a, 2013b), and that movement strategies during sagittal plane activities do not predict movement strategies employed during other tasks (Jones, Herrington, Munro, & Graham-Smith, 2014; Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014; J. B. Taylor et al., 2016). Considering that both basketball and soccer are multi-directional sports that require a large frequency of movements outside of the sagittal plane, strictly sagittal plane tasks may not provide a comprehensive view of high-risk biomechanics in these athletes. As such, biomechanical analyses of activities outside of the sagittal plane may be particularly important in women's basketball players, because they more often perform lateral movements than sagittal plane movements (Matthew & Delextrat, 2009), and more often perform lateral movements than soccer players over the course of a standard competition (Bloomfield et al., 2007).

Therefore, the purpose of this study was to better characterize hip and knee biomechanics (peak joint angles, joint excursions, external joint moments, and energetics) between competitive female basketball and soccer players during a standard double-leg screening test in the sagittal plane and during double- and single-leg jump landing tasks in the frontal plane. Based on previous biomechanical analyses of sagittal plane activities (Cowley et al., 2006), we hypothesized that there would be minimal differences in lower extremity kinematics, but that basketball players would generate higher hip and knee joint moments and stiffness measures than soccer players. Further, we anticipated that these relationships would be more prevalent during frontal than sagittal plane and single- than double-leg jump landings.

Methods

Participants

Ninety-nine female athletes participated in the study. In order to be included, participants were required to 1) be middle and high school athletes between 13-19 years of age, 2) consider basketball or soccer as their primary sport, 3) be fully cleared to participate in sports, and 4) have no lower extremity injury at time of testing. Potential participants were excluded if they reported a lower extremity surgery within the past 6 months, or had been previously diagnosed with a vestibular, balance, or cardiac disorder. Participants were enrolled in the study after providing written informed parental consent, and participant assent on forms approved by the Institutional Review Boards at the primary author’s institutions. Ten athletes that participated in the study were excluded from this analysis because they had actively participated in both basketball and soccer during the previous academic year, leaving a total of 89 single sport participants (n=40 basketball, n=49 soccer) in this study.

All participants were tested during their off-season, yet were still practicing with their teams. Each athlete completed an electronic questionnaire utilizing REDCap electronic capture tools (Harris et al., 2009) to determine the athlete's sport history, including the number of years, months per year, and days per week that they typically participate in their primary sport.

Instrumentation

Each subject was instrumented for three-dimensional analysis with 43 retroreflective markers on their trunk, pelvis, upper and lower extremities as has been previously published (J. B. Taylor et al., 2016). To standardize footwear, all participants donned laboratory provided athletic footwear not specific to either sport (adidas® adipure 360.2, Beaverton, Oregon, USA). After instrumentation, a static trial in anatomic neutral stance was collected to determine each subject's neutral alignment and anatomically define each body segment, by which subsequent biomechanical measures were referenced. Three-dimensional motion data, sampled at 200 Hz, were collected with Cortex software (version 5, Motion Analysis Corporation, Santa Rosa, CA, USA) using a 14-camera system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA, USA). Kinetic data, sampled at 1200 Hz, were collected by dual, in-ground, multi-axis force plates (AMTI, Watertown, MA, USA) such that each force plate collected data from a single leg.

Procedures

Because an overhead target can promote higher efforts during maximal vertical jump tests (Ford et al., 2005), a ball was placed directly over the force plates at the participant's maximal vertical jump reach. This height was determined by having participants perform 3-5 repetitions of a maximal effort double-leg countermovement jump prior to testing. Participants then completed three trials of five different jump landing tasks in random order (Figure 4.1 and 4.2): 1) DVJ, 2) double-leg forward jump and maximum countermovement jump in the sagittal plane (SAG-DL), 3) single-leg forward hop and maximal countermovement hop in the sagittal plane (SAG-SL), 4) double-leg lateral jump and maximum countermovement jump in the frontal plane (FRONT-DL), 5) single-leg lateral hop and maximum countermovement hop in the frontal plane (FRONT-SL). The DVJ is the gold standard jump landing screening task used in clinical practice and research and has evidence that the biomechanical movement patterns it elicits may be predictive of ACL injury (Hewett et al., 2005). The other four tasks were selected based on their good to excellent reliability and day-to-day performance consistency (J. B. Taylor et al., 2016), and their basketball-specific demands that are consistent with the single-leg and frontal plane jump landings that occur during competition and at time of ACL injury (Boden et al., 2009; Krosshaug et al., 2007; Matthew & Delextrat, 2009). Each participant performed 1-3 practice trials of each jump landing, until the subject was comfortable with the task and the investigator deemed the performance adequate. After the practice trials, each task was performed three times while lower extremity biomechanics were recorded for analysis. To avoid fatigue, athletes were given self-selected rest intervals ranging from 10-20 seconds between jumps and 60-90 seconds between tasks.

The DVJ was performed with the participant standing on top of a 31-cm box with their feet spaced 35-cm apart. Participants were instructed to drop straight down, land evenly on both feet and immediately perform a maximal-effort double-leg countermovement jump, reaching for the target with both hands. For the SAG-DL task, participants started a distance equal to their leg length (greater trochanter to lateral malleolus) away from the front edge of the force plates. Participants were then instructed to jump forward with both feet, aiming to land symmetrically with each foot on a separate force plate and immediately perform a maximal countermovement jump, reaching up for the target with both hands. Similar methods were used for the SAG-SL task, though the subject was positioned a distance equal to one-half of their leg length away from the force plates and were asked to hop off a single-leg, land on the same leg and immediately perform a maximal countermovement hop, attempting to reach the target with the contralateral hand. The contralateral upper extremity was used as the reaching arm because it most resembled athletic movements of multi-directional jumping sports. The SAG-SL task was performed three times on each leg in randomized order.

The FRONT-DL task was a lateral jump with double-leg landing and immediate maximal countermovement jump. The subject was positioned such that they were straddling a line placed a distance equal to one-half of their leg length away from the lateral edge of the nearest force plate. The subject was then instructed to keep their trunk facing forward and jump laterally such that each foot landed simultaneously on a separate force plate and immediately perform a maximal countermovement jump, reaching for the target with both hands. Similar techniques were used for the FRONT-SL task. Subjects were again placed at a distance equal to one-half of their leg length away from the closest force plate, standing on their outside leg. The subject was instructed to hop to the middle of the second force plate (located 36 cm plus one-half of leg length away), land on the opposite limb, and immediately perform a maximal countermovement hop, reaching toward the target with the hand contralateral to the landing limb.

Limb Dominance. Lower extremity biomechanics from each subject's dominant limb were used for analysis. The definition of limb dominance may vary between sports, especially considering the different sport-specific demands associated with basketball and soccer. Thus, rather than using the standard definition based on kicking leg preference, limb dominance was defined in this study based on performance during a triple hop for distance test. Participants were instructed to perform three consecutive maximal forward hops on the same limb without hesitation. One to three practice trials were given (self-selected) on each leg, and the next three subsequent test trials were recorded by measuring distance from the starting line to the point of toe contact upon completing the third hop. The order of limbs was counterbalanced for each subject. Trials were repeated if the participant lost balance or contacted the ground with their opposing leg at any instance throughout the test. Three trials on each leg were recorded and the leg which produced the longest maximal hop was subsequently defined as the dominant limb.

Data Analysis and Reduction

Biomechanical data were processed in Visual3D (Version 5, C-Motion, Inc., Rockville, MD, USA) with custom MATLAB (Version 8.0, The Mathworks, Natick, MA) code. Hip joint centers were calculated using the Bell method (Bell et al., 1990), and the knee and ankle joint centers were calculated as the centroid position of the medial and lateral femoral epicondyles and malleoli, respectively. Joint angle and moment data were subjected to a low-pass fourth-order Butterworth filter with a cutoff frequency of 12 Hz. Hip flexion, adduction, and internal rotation and knee extension, adduction, and internal rotation were reduced as positive motions.

Kinematic variables of interest were peak angles for hip flexion, adduction, and internal rotation, and knee flexion, abduction, internal rotation and external rotation and joint excursions for hip flexion, adduction, and internal rotation and knee flexion, abduction, internal and external rotation. Joint excursions were calculated by subtracting the angle at initial contact (first point that GRF surpasses 10N) from the peak angle during the landing phase (initial contact to maximal descent of the center of gravity). Kinetic variables included peak external moments (hip flexion, adduction and internal rotation, and knee flexion, abduction, internal rotation and external rotation) that were normalized to height and mass (N*m / m*kg). Joint energetics, including sagittal plane hip and knee energy absorption and torsional joint stiffness were also analyzed. To calculate energy absorption, net joint powers for each time point were first calculated (normalized joint moment * joint angular velocity) separately for hip and knee flexion. The area under the negative portion of the joint power curve was defined as the energy absorption that occurred by the hip and knee extensors [J/(N*m); reported as positive values for interpretation]. Torsional joint stiffness was calculated as the change in sagittal plane net moment divided by joint excursion during the landing phase at both the hip and the knee [N*m/(N*m*degrees)]. These biomechanical variables were selected based on their potential to contribute to injurious mechanics at the time of ACL injury in female athletes (Boden et al., 2009; Hashemi et al., 2011; Hewett et al., 2009; Krosshaug et al., 2007; Quatman & Hewett, 2009; Schmitz et al., 2009). Means of all successful trials for each task were calculated and used in statistical analyses. Trials were excluded if the athlete did not land on the intended force plate or if tracking markers were covered and unidentifiable during a trial, which accounted for less than 5% of trials in this study. To enable visual comparisons of the sport differences during each task, ensemble curves of select variables were generated in MATLAB by normalizing each variable to the duration of ground contact during the task.

Statistical Analyses

Anthropometric differences between basketball and soccer players were identified using independent t-tests. Then, four separate multivariate analysis of variance (MANOVA) models were performed to test for differences in: 1) peak angles, 2) excursions, 3) joint moments, and 4) energetics between basketball and soccer players for each task. Multivariate statistical significance was analyzed using Wilk's Lambda followed up with post-hoc pairwise comparison using independent t-tests as appropriate. Cohen's *d* effect sizes were calculated for all significant biomechanical differences between basketball and soccer players. Statistical significance was set *a priori* for all analyses at α=.05.

Results

Descriptive anthropometric and activity history data are reported in Table 4.1. Although there was no significant difference in age between basketball and soccer participants (p=.83), basketball players were taller (p<.001), heavier (p<.001), and had higher BMI (p=.01). Basketball players had fewer years of experience participating in their sport than soccer players (p<.001), but there were no differences in current training volume (p>.05).

Biomechanical Comparisons

Means and standard deviations of all hip and knee kinematic, kinetic, and energetic data are reported for each jump landing task in Tables 4.2 and 4.3.

Kinematics. There were no significant differences between sports in peak kinematic variables for any of the double-leg landings (DVJ: λ=.91, p=.32; SAG-DL: λ=.91, p=.40; FRONT-DL: λ=.86, p=.08); however, significant differences were identified during single-leg landings (SAG-SL: λ=.83, p=.03; FRONT-SL: λ=.75, *p*=.001), where basketball players landed with greater peak hip flexion angles during the SAG-SL (*p*=.04, *d*=0.45), and lesser hip adduction angles during the FRONT-SL (*p*<.001, *d*=0.82) task.

Sport differences in total joint excursion were identified during each jump landing task (DVJ: λ=.84, *p*=.04; SAG-DL: λ=.80, *p*=.01; SAG-SL: λ=.79, *p*=.006; FRONT-DL: λ=.80, *p*=.009; FRONT-SL: λ=.76, *p*=.002). These differences were predominantly found in sagittal plane joint motions (Figure 4.3), where basketball players went through less hip flexion during the DVJ (*p*=.047, *d*=0.43), SAG-DL (*p*=.002, *d*=0.69), FRONT-DL (*p*<.001, *d*=0.82), FRONT-SL (*p*=.03, *d*=0.48) and less knee flexion during the SAG-DL (*p*=.002, *d*=0.70), SAG-SL (*p*=.003, *d*=0.65), FRONT-DL (*p*<.001, *d*=0.80), and FRONT-SL (*p*=.01, *d*=0.56) task. Basketball players also went through greater relative knee external rotation during the DVJ (*p*=.05, *d*=0.42), and internal rotation during the SAG-SL (*p*=.05, *d*=0.43) than soccer players. In the FRONT-SL task (Figure 4.4), basketball players (in addition to less hip and knee flexion already noted) went through more hip internal rotation (*p*=.003, *d*=0.67), knee external rotation (*p*=.001, *d*=0.76), and less knee internal rotation (*p*=.005, *d*=0.62) than soccer players..

Kinetics. No significant differences in joint moments were found during double-leg landings (DVJ: λ=.90, *p*=.29; SAG-DL: λ=.90, *p*=.27; FRONT-DL: λ=.86, *p*=.09;), yet significant differences were identified during the SAG-SL (λ=.85, *p*=.05) and FRONT-SL (λ=.75, *p*=.001) tasks. Specifically, during the SAG-SL task, basketball players had greater hip internal rotation (*p*=.02, *d*=0.55) and knee abduction (*p*=.02, *d*=0.47) moments and greater knee abduction (*p*=.003, *d*=0.76), less hip adduction (*p*=.001, *d*=0.71) and less knee external rotation moments (*p*<.001, *d*=0.78) during the FRONT-SL task than soccer players (Figure 4.4).

Energetics. Significant differences in hip and knee energetics were identified during the FRONT-DL task (λ=.77, *p*<.001), such that basketball players absorbed less energy at their hip (*p*<.001, *d*=0.94), and exhibited greater stiffness at the hip (*p*<.001, *d*=0.80) and knee (*p*=.001, *d*=0.67) than soccer players. No significant differences in energetics were identified during the DVJ (λ=.91, *p*=.10), SAG-DL (λ=.89, *p*=.055), SAG-SL (λ=.96, *p*=.42), or FRONT-SL (λ=.91, *p*=.09) tasks.

Discussion

Both women's basketball and soccer have relatively high ACL injury rates (Hootman et al., 2007), but basketball players may be more at risk for non-contact injuries (Agel et al., 2005), and current prevention programs have been much less successful at reducing the risk of ACL injury in women's basketball (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007; J. B. Taylor, Ford, Nguyen, Terry, & Hegedus, 2015). Because ACL injury prevention programs are designed to improve neuromuscular strategies to reduce high-risk movements, the lower success of these programs in basketball suggests that either the training program is less effective at modifying high-risk biomechanics in basketball than soccer players, or that women's basketball and soccer players employ different biomechanical profiles and may need sport-specific training to address these distinct movement strategies. Our findings indicate it may be the latter, as we observed a number of fundamental differences in movement strategies in female basketball and soccer athletes.

Table 4.4 provides an overall summary of the primary differences between women's basketball and soccer athletes. Our results indicate that soccer players tend to land with an overall more protective biomechanical strategy than basketball players. Specifically, basketball players consistently landed more stiffly, with less hip and knee flexion excursion, and during some tasks were more likely to land with greater hip internal rotation and knee external rotation angles and greater knee abduction moments, which are commonly considered elements of dynamic knee valgus. These sport-specific biomechanical differences were more pronounced when the intensity and complexity of the task increased from double- to single-leg and sagittal to frontal plane activities. These findings expand upon previous work that has reported larger forces (Cowley et al., 2006) and knee valgus measures (A. Munro et al., 2012) during standard sagittal plane jump landings in women's basketball compared to soccer players.

Shallow knee and hip flexion angles have been implicated as a risk factor for ACL injury (Boden et al., 2009; Hashemi et al., 2011; Shimokochi & Shultz, 2008). In our study, basketball players consistently displayed a stiffer landing strategy regardless of task, but this difference approached 10 degrees less hip and knee flexion motion during the FRONT-DL task. This may place basketball players at higher risk for ACL injury, because observational video analyses have reported that up to 90% of injured female athletes land with less than 30 degrees of knee flexion at initial contact and exhibit relatively low knee flexion excursions from initial contact to the estimated onset of ACL rupture (Cochrane et al., 2007; Krosshaug et al., 2007; Olsen et al., 2004). This is also consistent with cadaveric and in vivo studies of ACL strain that report increased strain on the ACL between 0-30 degrees of knee flexion (D. L. Butler, Noyes, & Grood, 1980; Sakane et al., 1999) and that knee flexion best predicts ACL strain (Cerulli, Benoit, Lamontagne, Caraffa, & Liti, 2003; Shin, Chaudhari, & Andriacchi, 2007; K. A. Taylor et al., 2011; Weinhold et al., 2007; Withrow, Huston, Wojtys, & Ashton-Miller, 2006). Although shallow knee flexion angles and excursions have been reported at the time of ACL injury, no study has prospectively linked this movement strategy during a screening test to risk of subsequent injury. However, due to the overwhelming evidence supporting stiff-legged landings as a potential mechanism for ACL injury, our results indicate that basketball players may be at higher risk of injury during jump landing activities. While ACL injury prevention programs already focus on increasing knee flexion and landing softly (LaBella et al., 2011), sports medicine professionals may need to place greater emphasis on these strategies when training basketball players.

Although hip and/or knee joint excursions tended to be less in all tasks in female basketball players, sport differences in peak angles, moments, and energetics were mostly limited to frontal plane movements and single-leg landings. Previous studies comparing basketball and soccer players have only tested athletes during sagittal plane jump landings. Using a DVJ, Cowley et al. (2006) reported higher vertical ground reaction forces over less time in basketball players, but minimal differences in kinematics or joint moments were identified between the two sets of athletes. Munro et al.(2012) were limited to two-dimensional analysis and used a single-leg drop landing, as opposed to a hop, although they were able to identify differences in frontal plane projection angles. Our study provides a more comprehensive biomechanical comparison of basketball and soccer athletes, which may begin to elucidate why injury prevention programs are less successful in basketball athletes. Frontal plane movements, such as lateral shuffling, occur more frequently than running in women's basketball (Matthew & Delextrat, 2009). Additionally, basketball players often land asymmetrically (Ford et al., 2003; Herrington, 2011), and due to the physical nature of the sport, are often perturbed prior to landing, potentially influencing their risk for injury (Krosshaug et al., 2007). Thus, while most biomechanical analyses of injury risk and the adaptations following ACL injury prevention programs use standard double-leg tasks, our results indicate that a more comprehensive screen, including more complex tasks that incorporate frontal plane and single landings are crucial in future investigations of populations that include women's basketball players.

Of all the jump landing tasks used in this study, the DVJ has the most evidence supporting its use for ACL injury risk screening (Hewett et al., 2005), yet the FRONT-SL task was able to best discriminate between the biomechanical differences of basketball and soccer players. Although this task has not yet been validated, it has been shown to be a reliable task that provides additional complementary information to standard double-leg landings in the sagittal plane that may help create a more complete biomechanical profile (J. B. Taylor et al., 2016). It also may be a task more representative of what occurs at the time of ACL injury. ACL injuries have been linked to single-leg ground contact, decelerating movements and change of directions (Boden et al., 2009; Hewett et al., 2009; Krosshaug et al., 2007), but the plane of movement has not been specifically studied. Observational video analyses of injured athletes have reported that athletes at the time of injury have trended to land with and stay in more hip abduction (27-30^{o}) and ipsilateral lateral trunk lean (11^{o}) than matched controls (Boden et al., 2009; Hewett et al., 2009). While the reason for hip abduction in these cases is unknown, these values may suggest that the athletes were abducting their hip to widen the base of support in anticipation of a frontal plane change of direction. This again suggests that investigating the biomechanics of frontal plane landings may be extremely important during future injury risk studies.

Kinematically, the combination of less sagittal plane hip and knee flexion excursion, and greater transverse plane motion that was evident in women's basketball players is indicative of motions typically associated with dynamic lower extremity valgus, which may increase their risk of ACL injury. Consistent with this premise, basketball players had greater knee abduction moments (KAM) than soccer players during single-leg tasks, which has been reported to be predictive of ACL injury risk, albeit produced during a DVJ (Hewett et al., 2005). Consistently landing with a stiff knee, in relatively low hip and knee flexion excursions, and higher KAM during these tasks may in part contribute to the heightened risk of non-contact ACL injury in basketball players, especially because basketball requires more frequent single-leg jump landings and frontal plane movements than soccer (Bloomfield et al., 2007; Matthew & Delextrat, 2009). Because ACL injury prevention programs emphasize sagittal plane movements and double-leg landings, they may not provide the appropriate stimulus to improve high-risk biomechanics during frontal plane, single-leg activities that is necessary to reduce risk in female basketball players. While basketball players often train to increase performance in the frontal plane (i.e. quickness in lateral shuffling), our results suggest that additional technique training and feedback may be warranted to increase knee and hip flexion angles and promote frontal and transverse plane hip and knee stability during these types of motions.

In summary, ACL injury prevention programs have been broadly administered to multi-directional sport athletes, but with substantially greater success in soccer than basketball. Despite these findings, there has been a lack of basketball-specific injury prevention research to understand the poor efficacy of these programs in basketball (O'Brien & Finch, 2014). Our results indicate that basketball and soccer players exhibit distinct biomechanical profiles during a variety of movement tasks, suggesting there needs to be greater consideration for their distinct sport demands and movement strategies when implementing rehabilitation, screening, or injury prevention programs. Specifically, basketball players may need a stronger emphasis placed on softer landing strategies to reduce forces and limit ACL strain that occurs at shallow knee flexion angles. Additionally, basketball players may benefit from dedicated technique training during single-leg and frontal plane jump landings. While basketball-specific training that incorporates movements outside of the sagittal plane is prevalent during rehabilitation and return to sport procedures (Waters, 2012), this type of training has previously been lacking from ACL injury prevention programs that typically use a “one size fits all” approach without accounting for sport-specific demands.

Limitations

The tasks used in this study can be reliably performed and have the potential to provide complementary information to standard screening tasks (J. B. Taylor et al., 2016). However, other than the DVJ, these tasks have yet to be validated as effective prospective screening tools for ACL injury risk. Future research is needed to study the predictive ability of one or a combination of these tests to identify athletes at risk for subsequent ACL injury. Additionally, this study was limited to characterizing sport-specific biomechanical differences during more basketball-specific tasks to help explain differences in injury rates and the success of ACL injury prevention programs in these two sports. Although basketball consists of more jumping and frontal plane activities than soccer, soccer too has sport-specific demands, including cutting and change of direction that are more prevalent than basketball. Thus, while this study now illustrates the biomechanical differences during jump landings, it did not analyze biomechanical sport differences during cutting activities, which may further help describe sport-specific biomechanical profiles. A previous study reported that soccer players exhibit greater ground reaction forces and decreased stance time during 45 degree side-step cuts than basketball players, but further work may be warranted to address differences at various cutting and pivoting angles, considering that cutting at different angles can elicit distinct and unrelated movement strategies (Jones et al., 2014).

Conclusion

Adolescent female basketball and soccer players exhibit distinct biomechanical profiles during a variety of single and double-leg jump landing tasks in the sagittal and frontal plane. Basketball players land with more prevalent high-risk movement strategies, including a consistent strategy of stiff landings with decreased hip and knee flexion excursions. During various tasks, basketball players also exhibit greater knee external rotation excursions, and hip internal rotation and knee abduction moments that may place them at a higher risk of injury during single-leg and frontal plane jumping activities. Results of this study indicate that future biomechanical risk factor screening and injury prevention programs may need to take a more sport-specific approach to identifying those at risk and designing appropriate neuromuscular training exercise to optimally reduce the potential for injury in both female basketball and soccer players.

Tables and Figures

Figure 4.1. Sagittal Plane Jump Landing Tasks Used in this Study, Including the Beginning and Landing Phase of the DVJ (A,B), SAG-DL (C,D), and SAG-SL (E,F).

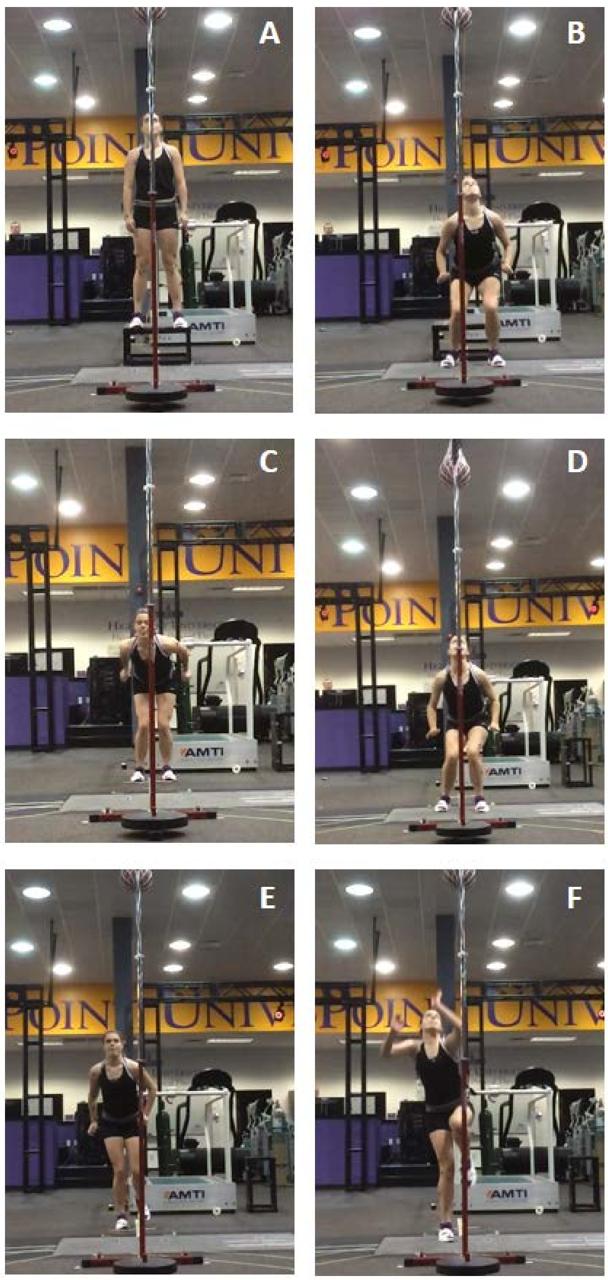


Figure 4.2. Frontal Plane Jump Landing Tasks Used in this Study, Including the Beginning and Landing Phase of the FRONT-DL (A,B), and FRONT-SL (C,D).

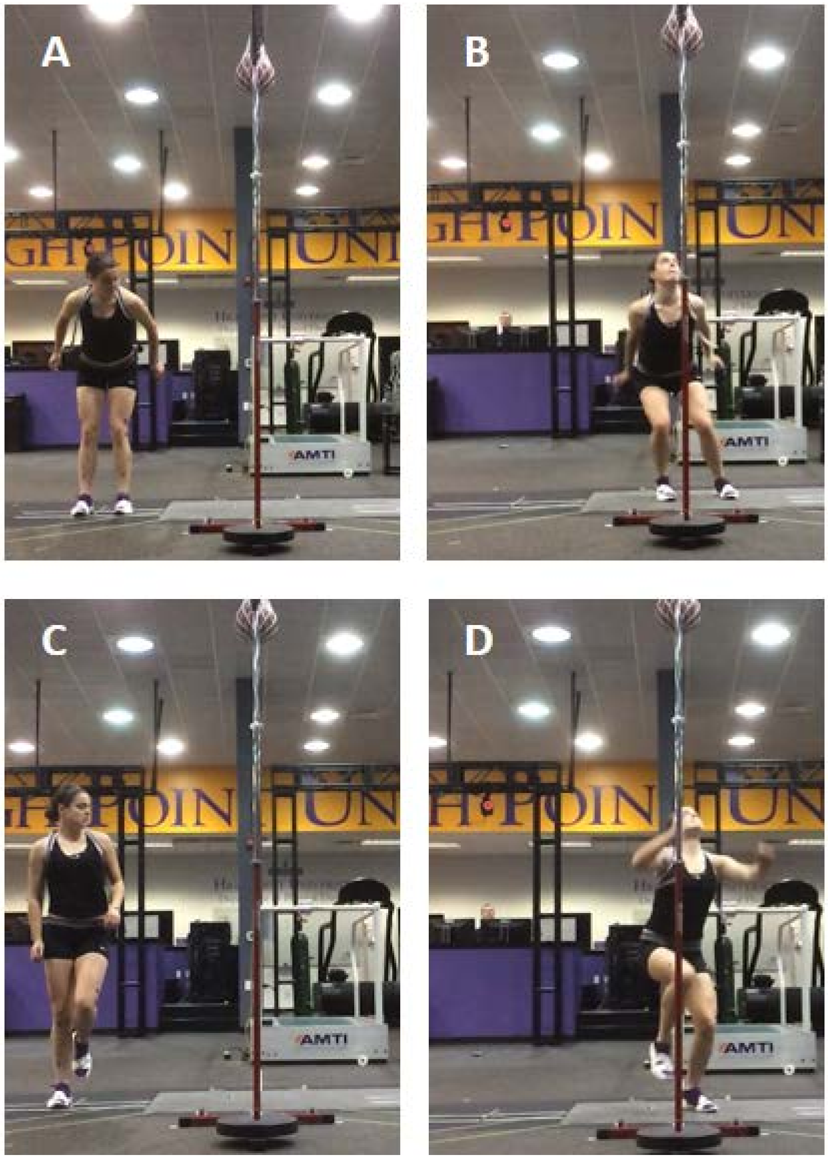


Figure 4.3. Ensemble Curves of a) Hip and b) Knee Flexion Angles for Each Jump Landing Task.

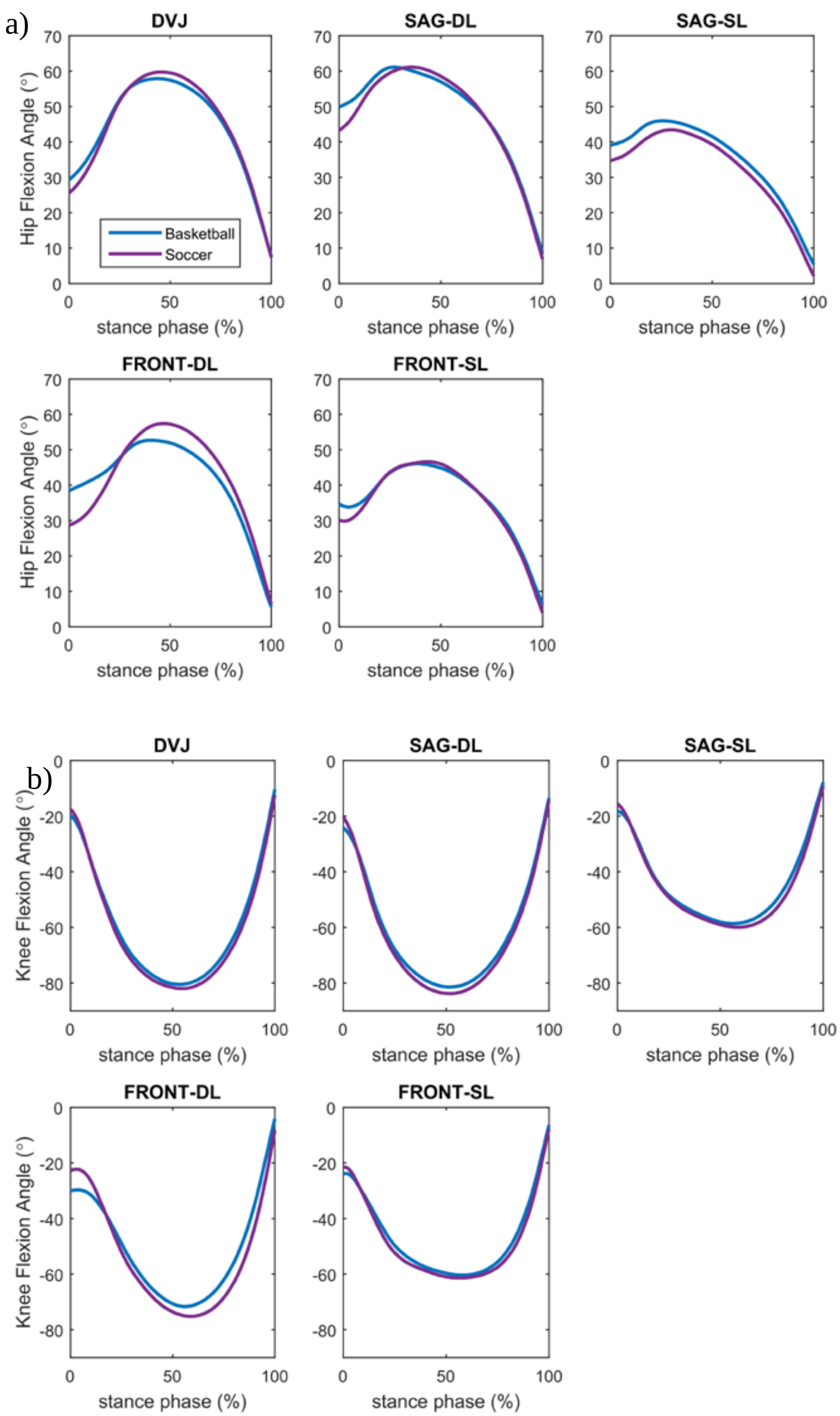


Figure 4.4. Ensemble Curves of Frontal and Transverse Plane Angles and Moments at the Hip and Knee During the FRONT-SL task. (abd = abduction, add= adduction, IR =internal rotation, ER = external rotation)

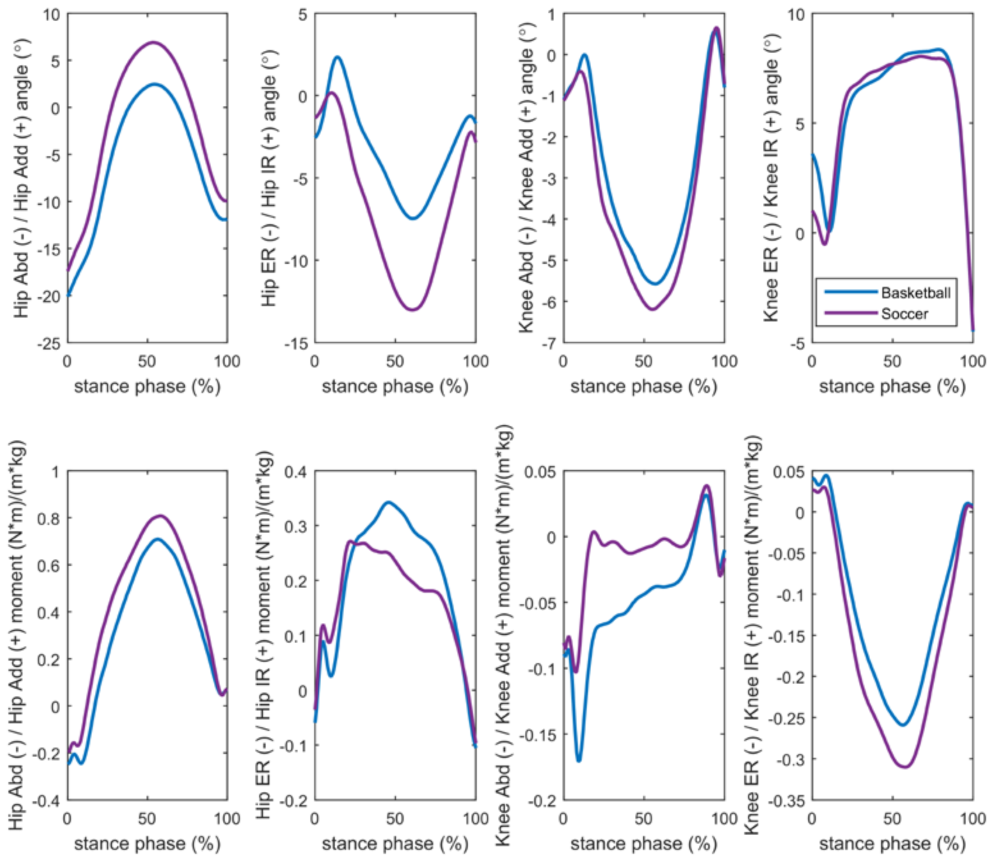


Table 4.1. Means ± Standard Deviations (SD) of Anthropometric and Sport History Variables.

	Basketball	**Soccer**	**p-value**
Age (years)	15.6 ± 1.3	15.5 ± 1.3	.83
Height (m)	1.70 ± 0.07*	1.64 ± 0.05*	*<.001*
Mass (kg)	65.1 ± 11.3*	56.6 ± 6.5*	*<.001*
BMI (kg/m^2)	22.6 ± 3.2*	21.1 ± 2.1*	*.01*
Sport History			
- Years Played	7.7 ± 2.5*	9.5 ± 2.2*	*<.001*
- Months per year	10.8 ± 1.6	11.0 ± 1.5	.64
- Days per week	4.3 ± 1.4	4.4 ± 0.9	.63

* significant difference between basketball and soccer players (*p*<.05).

Table 4.2. Means ± SD of Kinematic Variables for Each Jump Landing Task for Basketball (BB) and Soccer (SOC) Players.

		Sport	DVJ	SAG-DL	SAG-SL	FRONT-DL	FRONT-SL
Peak Angles (degrees)	Hip Flexion (+)	BB	59.1±10.2	63.5±6.9	***48.0±7.2****	55.2±8.5	47.7±7.4
		SOC	60.3±9.4	62.7±8.3	***44.7±7.6****	57.2±9.7	47.6±7.1
	Hip Adduction (+)	BB	2.1±5.5	1.2±4.9	9.5±5.0	-2.9±6.9	***1.3±6.2†***
		SOC	1.4±4.9	1.5±4.8	10.3±4.7	-4.2±5.3	***6.2±5.8†***
	Hip IR (+)	BB	-3.3±6.4	-1.1±8.3	-2.0±6.6	3.6±8.7	4.5±8.1
		SOC	-5.4±5.2	-3.3±6.4	-2.7±8.0	2.2±7.4	3.5±7.7
	Knee Flexion (-)	BB	-80.5±7.9	-80.8±7.8	-56.0±6.4	-71.1±7.7	-58.5±5.7
		SOC	-81.6±8.6	-82.9±8.9	-56.9±6.8	-73.6±7.9	-60.0±5.7
	Knee Abduction (-)	BB	-8.9±6.6	-8.4±6.7	-5.5±5.9	-8.0±6.2	-6.6±5.7
		SOC	-8.1±6.1	-7.5±6.1	-4.6±4.9	-6.8±5.4	-5.8±5.0
	Knee ER (-)	BB	-0.6±5.5	0.3±6.4	-0.5±5.6	-1.2±5.9	-1.9±6.3
		SOC	-1.9±5.4	-1.6±5.5	-1.1±5.0	-4.8±5.8	-2.3±5.2
	Knee IR (+)	BB	9.2±6.2	11.1±6.0	9.5±4.6	10.1±6.1	9.3±5.3
		SOC	8.4±6.0	9.6±5.6	9.9±5.1	7.6±6.2	9.4±5.7
Excursion (degrees)	Hip Flexion	BB	***30.3±10.4†***	***13.5±7.3†***	8.8±5.0	***21.9±11.8†***	***13.2±9.2†***
		SOC	***34.8±10.5†***	***19.4±9.8†***	10.1±5.9	***31.5±11.7†***	***17.4±8.3†***
	Hip Adduction	BB	4.6±3.6	4.4±3.6	9.9±4.0	4.8±5.2	21.7±5.8
		SOC	3.2±3.6	4.1±3.4	11.4±4.7	4.7±6.2	23.4±5.4
	Hip IR	BB	5.2±3.9	7.6±5.8	7.6±4.3	10.9±7.5	***7.4±4.7****
		SOC	3.6±4.1	5.5±5.0	6.7±3.8	9.5±5.7	***4.6±3.7****
	Knee Flexion	BB	61.2±8.7	***57.2±8.5†***	***37.6±6.5†***	***44.8±12.4†***	***34.2±8.9†***
		SOC	64.7±8.9	***63.7±10.0†***	***41.7±6.1†***	***53.7±9.8†***	***38.7±7.1†***
	Knee Abduction	BB	8.9±5.3	8.3±4.9	4.7±3.7	7.5±5.9	5.1±3.4
		SOC	8.1±4.6	7.9±4.4	4.0±3.2	8.0±5.0	5.0±3.1
	Knee IR	BB	7.0±5.9	7.2±5.4	***6.1±4.9†***	6.9±6.0	***5.6±4.9†***
		SOC	8.6±5.5	8.8±5.4	***8.0±3.9†***	8.1±5.3	***8.5±4.5†***
	Knee ER	BB	***3.6±4.2****	4.5±4.7	3.9±3.4	5.7±6.7	***5.7±3.9****
		SOC	***2.1±3.0****	2.7±4.0	3.0±3.1	5.3±6.3	***3.1±2.9****

IR – internal rotation; ER – external rotation
* basketball significantly greater motion than soccer (*p*<.05)
† soccer significantly greater motion than basketball (*p*<.05)

Table 4.3. Means ± SD of Kinetic Variables for Each Jump Landing Task for Basketball (BB) and Soccer (SOC) Players.

		Sport	DVJ	SAG-DL	SAG-SL	FRONT-DL	FRONT-SL
Peak External Moments (N*m)/(m*kg)	Hip Flexion (+)	BB	1.03±0.23	1.22±0.27	1.74±0.39	1.15±0.31	1.27±0.34
		SOC	1.03±0.22	1.21±0.29	1.63±0.36	1.17±0.29	1.37±0.28
	Hip Adduction (+)	BB	0.19±0.13	0.16±0.16	0.99±0.23	0.06±0.19	***0.60±0.24†***
		SOC	0.19±0.13	0.17±0.16	1.03±0.22	0.10±0.16	***0.75±0.18†***
	Hip IR (+)	BB	0.26±0.08	0.32±0.11	***0.43±0.11****	0.32±0.11	0.42±0.16
		SOC	0.26±0.08	0.31±0.10	***0.37±0.11****	0.37±0.12	0.39±0.11
	Knee Flexion (-)	BB	-1.11±0.20	-1.24±0.21	-1.59±0.26	-1.31±0.27	-1.29±0.24
		SOC	-1.06±0.22	-1.25±0.24	-1.63±0.30	-1.24±0.38	-1.33±0.24
	Knee Abduction (-)	BB	-0.27±0.13	-0.26±0.13	***-0.17±0.17****	-0.32±0.16	***-0.28±0.11****
		SOC	-0.22±0.13	-0.23±0.13	***-0.10±0.13****	-0.28±0.20	***-0.20±0.10****
	Knee ER (-)	BB	-0.04±0.05	-0.04±0.06	-0.36±0.11	-0.03±0.07	***-0.24±0.10†***
		SOC	-0.05±0.05	-0.04±0.05	-0.38±0.08	-0.05±0.07	***-0.31±0.08†***
	Knee IR (+)	BB	0.11±0.06	0.14±0.08	-0.002±0.03	0.16±0.08	0.08±0.05
		SOC	0.09±0.06	0.11±0.06	-0.009±0.02	0.14±0.07	0.06±0.05
Energetics	Hip Energy Absorption (J/(N*m))	BB	0.017±0.007	0.011±0.005	0.016±0.008	***0.011±0.007†***	0.013±0.008
		SOC	0.020±0.008	0.015±0.007	0.016±0.009	***0.019±0.010†***	0.017±0.008
	Knee Energy Absorption (J/(N*m))	BB	0.065±0.013	0.077±0.022	0.054±0.016	0.044±0.015	0.038±0.013
		SOC	0.066±0.015	0.082±0.017	0.055±0.015	0.049±0.017	0.045±0.012
	Hip Joint Stiffness (N*m/(N*m*degrees))	BB	0.005±0.002	0.018±0.023	0.028±0.033	***0.010±0.006****	0.019±0.022
		SOC	0.004±0.001	0.010±0.011	0.024±0.043	***0.006±0.004****	0.012±0.010
	Knee Joint Stiffness (N*m/(N*m*degrees))	BB	0.002±0.001	0.003±0.001	0.006±0.002	***0.004±0.002****	0.005±0.002
		SOC	0.002±0.001	0.003±0.001	0.005±0.001	***0.003±0.001****	0.004±0.001

IR – internal rotation; ER – external rotation
* basketball significantly greater than soccer (*p*<.05)
† soccer significantly greater than basketball (*p*<.05)

Table 4.4. Summary Table Showing Biomechanical Differences Between Basketball and Soccer Players. All motions are considered positive motions for ease of comparison.

	DVJ	**SAG-DL**	**SAG-SL**	**FRONT-DL**	**FRONT-SL**
Kinematics					
Hip Flexion			↑		
Hip Adduction					↓
Hip IR					
Knee Flexion					
Knee Abduction					
Knee ER					
Knee IR					
Excursions					
Hip Flexion	↓	↓		↓	↓
Hip Adduction					
Hip IR					↑
Knee Flexion		↓	↓	↓	↓
Knee Abduction					
Knee ER	↑				↑
Knee IR			↓		↓
Joint Moments					
Hip Flexion					
Hip Adduction					↓
Hip IR			↑		
Knee Flexion					
Knee Abduction			↑		↑
Knee ER					↓
Knee IR					
Energetics					
Hip Energy Absorption				↓	
Knee Energy Absorption					
Hip Joint Stiffness				↑	
Knee Joint Stiffness				↑	

IR: internal rotation, ER: external rotation
↑ : greater in basketball players than soccer players (p<.05)
↓: lesser in basketball players than soccer players (p<.05)

CHAPTER V

MANUSCRIPT II

Title

Effects of an ACL injury prevention program on lower extremity biomechanics during multi-directional jump landings: A randomized controlled trial.

Abstract

Context

Anterior cruciate ligament (ACL) injury prevention programs may reduce the risk of injury by modifying high-risk lower extremity biomechanics during double-leg sagittal plane landing tasks; however, the extent to which these mechanics are modified during multi-directional jump landing tasks is unknown.

Objective

To examine the extent to which an ACL injury prevention program modifies lower extremity biomechanics during single- and double-leg landings tasks in both the sagittal and frontal plane. We hypothesized that the training program would elicit greater improvements in lower extremity biomechanics during a double-leg sagittal plane landing task than tasks performed on a single-leg or in the frontal plane.

Design

Cohort study.

Setting

Biomechanics research laboratory, field-/court-based training program.

Patients or Other Participants

A total of 97 competitive multi-directional sport athletes that competed at the middle- or high-school level were cluster randomized into intervention (n=48, age=15.4±1.0 years, height=1.7±0.07 m, mass=59.9±11.0 kg) and control (n=49, age=15.7±1.6 years, height=1.7±0.06 m, mass=60.4±7.7 kg) groups.

Intervention(s)

An established 6-week warm-up based ACL injury prevention program. Three-dimensional biomechanical analyses of a double- (SAG-DL) and single-leg (SAG-SL) sagittal, and double- (FRONT-DL) and single-leg (FRONT-SL) frontal plane jump landing tasks were tested before and after the intervention.

Main Outcome Measure(s)

Peak angles, excursions, and external joint moments were analyzed for group differences using 2 (group) x 4 (task) repeated measures MANOVA models of delta scores (post – pre test value) (α<.05).

Results

Relative to the control group, no significant biomechanical changes were identified in the intervention group for any of the tasks (*p*>.05). However, a group by task interaction was identified for knee abduction (λ=.80, *p*=.02), such that participants in the intervention group showed relative decreases in knee abduction moments during the SAG-DL compared to the SAG-SL (*p*=.005; *d*=0.45, CI=0.04-0.85) task.

Conclusions

A 6-week warm-up based ACL injury prevention program resulted in no significant biomechanical changes during a variety of multi-directional sport activities.

Keywords

ACL, injury prevention, multi-directional sports, lower extremity biomechanics

Introduction

Anterior cruciate ligament (ACL) injuries continue to be a concern in women's athletics (Gornitzky et al., 2015). Seventy percent of ACL injuries occur via a non-contact mechanism, and of those, up to 70% may occur during decelerating, single-leg, change-of-direction activities, such as a cut, pivot, or single-leg jump landing (Boden et al., 2009; Krosshaug et al., 2007). Non-contact ACL injury rates are highest in multi-directional women's sports, with up to 3.7% of these athletes tearing their ACL each year (Gornitzky et al., 2015; Moses et al., 2012). Multi-directional sports require changes in activity or direction of movement every 2-3 seconds, and commonly demand movements outside of the sagittal plane. In some sports, such as basketball, more movements are performed in the frontal than sagittal plane during a standard competition (Matthew & Delextrat, 2009). Despite the multi-directional nature of these sports, ACL injury prevention programs have largely focused on sagittal plane movements.

To date, preventative training programs in women's multi-directional sports have generally been successful at lowering the risk of ACL injury in participating populations (J. B. Taylor, Waxman, et al., 2015). Prevention programs are conventionally performed as either a 20-30 minute on-field or on-court warm-up, or an isolated 60-90 minute workout, and have prescribed neuromuscular training in the form of strength, flexibility, agility and/or plyometric training (J. B. Taylor, Waxman, et al., 2015). Strength and flexibility training target specific lower extremity musculature, such as the hamstrings that have been identified to influence ACL injury risk (Ford et al., 2015). Agility and plyometric training focus more on motor control, utilizing progressions from low- to high-intensity exercises, combined with technique feedback, in an attempt to improve high-risk movement strategies, such as stiff-legged landings and dynamic lower extremity valgus (Ford et al., 2015; Hashemi et al., 2011; Hewett et al., 2005; Shimokochi & Shultz, 2008). In general, evidence supports that these programs do improve lower extremity strength and positively improve lower extremity biomechanics during cutting and double-leg jump landing tasks that occur in the sagittal plane (Hewett et al., 1996; Lephart et al., 2005; Lim et al., 2009; Pollard et al., 2006). However, the extent to which these findings translate to injury reduction in multi-directional athletes performing predominantly non-sagittal plane tasks is questionable.

Multiple recent meta-analyses have reported that current ACL injury prevention programs are more successful in soccer than other multi-directional sports such as basketball, despite similar injury and participation rates (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007; J. B. Taylor, Ford, et al., 2015). While one reason may be due to the lack of consistent research in the basketball population (O'Brien & Finch, 2014), it is also possible that ACL injury prevention programs are not designed to account for the large frontal plane demands, and potential mechanisms of injury, that occur during basketball competition. Of the ACL injury prevention programs that have been implemented in basketball players, exercises largely emphasize sagittal plane movements such as squats and lunges, while plyometric activities predominantly emphasize double-leg landings with primary movement in the sagittal plane, such as squat jumps, tuck jumps, and broad jumps (Hewett et al., 1999; LaBella et al., 2011; Pfeiffer et al., 2006). Literature in the strength and conditioning field largely supports the concept of specificity of training (Baechle & Earle, 2000), yet it is currently unknown whether ACL injury prevention programs that are largely based around sagittal plane movements are specific enough to modify lower extremity biomechanics during a variety of multi-directional sport specific tasks outside of the sagittal plane. Given these concerns, and the fact that evidence suggests that current programs still need to intervene in 89 athletes to prevent 1 ACL injury over the course of a competitive season, further research into the optimization of ACL injury prevention programs is warranted (Grindstaff, Hammill, Tuzson, & Hertel, 2006).

Thus, the purpose of this study was to examine the extent to which an established, successful warm-up based ACL injury prevention program modifies lower extremity biomechanics during single- and double-leg landings that occur with sagittal and frontal plane movements in female athletes. We hypothesized that the training program would elicit greater improvements in lower extremity biomechanics (increased hip and knee flexion and decreased hip adduction, hip internal rotation, knee abduction, knee internal and external rotation) during a double-leg sagittal plane landing task, as compared to tasks performed on a single leg or in the frontal plane.

Methods

Participants

This study is part of a larger study that examined sport-specific biomechanical adaptations after an ACL injury prevention program. Participants were recruited from three competitive basketball and soccer clubs to participate in the study. Interested participants were included in the study if they: 1) were 13-19 years old, 2) participated in middle or high school level competitive women's sport(s) and considered either basketball or soccer as their primary sport, 3) were cleared to participate in sports, and 4) had no lower extremity injury at time of testing. Middle and high school basketball and soccer athletes were chosen because of the large multi-directional demands in their sports and our intent to recruit a participant pool that had relatively little experience in ACL injury prevention training. Participants were excluded if they reported a previous lower extremity surgery within the past 6 months or had ever been previously diagnosed with a vestibular, balance, or cardiac disorder. All participants provided written informed parental consent and participant assent as approved by the Institutional Review Boards at the authors' institutions. After the initial testing session, if participants could not commit to completing the study in its entirety (6-week intervention with pre- and post-tests), they were excluded from further testing and analysis.

An *a priori* power analysis (G*Power, version 3.1.2) was performed to determine the appropriate sample size for the larger study, which dichotomized the control and intervention groups by sport. For this 4-group design, 20 participants per group was determined to be adequate to achieve 80% power at a statistical significance criterion of 0.05 with a moderate effect size (0.38). Ninety-nine participants were initially enrolled in the study, and 97 were eligible for the randomized controlled trial. As such, we had more than sufficient power to detect biomechanical changes in this 2-group design.
Participants were cluster randomized by team using an online random sequence generator into parallel intervention and control groups. Group allocation was kept in a concealed envelope and participants were informed of their group membership after their entire team completed the first testing session. Random allocation was performed by one member of the research team and all testing and training were performed by another investigator, allowing for blinded testing during the pre-, but not the post-testing sessions.

Data Collection

All participants completed identical testing sessions at two time points (pre- and post- test) in a biomechanics laboratory setting. Participants in the intervention group were tested within two weeks prior to the scheduled onset of the training program and re-tested between 2-10 days after the completion of the last training session. Participants in the control group were tested approximately 8 weeks apart. Each athlete completed an electronic questionnaire (REDCap™ software, Version 4.14) to identify the number of days that each athlete participated in their dominant sport to ensure similarities in activity levels between control and intervention groups.

Limb Dominance. Analyses was performed on each athlete's dominant limb, which for this study was defined as the side which produced the longest jump distance during a forward triple hop test (Hamilton et al., 2008). Participants performed 1-3 practice hops followed by three measured hops on each limb. The order of hops was counterbalanced for each subject. Distance was measured utilizing a standard cloth tape measure affixed to the ground to the point of toe contact upon completing the third hop. Trials were repeated if the participant lost balance, contacted the ground with their opposite limb, or hesitated between hops.

Instrumentation. Participants were instrumented for three-dimensional biomechanical analysis with 43 retroreflective markers on their trunk, upper and lower extremities as previously published (J. B. Taylor et al., 2016). Participants wore standardized footwear (adidas® adipure 360.2, Beaverton, Oregon, USA) throughout all testing sessions. Once instrumented, participants completed a static trial in neutral alignment, by which all subsequent biomechanical measures were referenced. Using Cortex software (version 5, Motion Analysis Corporation, Santa Rosa, CA, USA), three dimensional kinematic data, sampled at 200 Hz, were collected via a 14-camera system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA, USA) and kinetic data, sampled at 1200 Hz, were collected via dual, in-ground, 90 x 60 cm multi-axis force plates (AMTI, Watertown, MA, USA).

Procedures. All participants completed three trials of the following movements, which were each followed by a maximum countermovement jump (double-leg) or hop (single-leg): 1) double-leg sagittal plane forward jump (SAG-DL), 3) single-leg sagittal plane forward hop (SAG-SL), 4) double-leg lateral jump (FRONT-DL) and, 5) single-leg lateral hop (FRONT-SL). To encourage maximal effort during the maximum countermovement jump or hop, participants attempted to reach towards an overhead target during each task. The target was placed at each participant's maximal reach obtained during 3-5 trials of a double-leg countermovement jump prior to data collection.

The order of tasks was randomized for each participant, but were performed in the same order at the pre- and post-testing sessions. For the SAG-DL task, participants started at a distance equal to their leg length (greater trochanter to lateral malleolus) away from the front edge of the force plates. Participants were then instructed to jump forward, land simultaneously with both feet and immediately perform a maximal countermovement jump, reaching for the overhead target with both hands. For the SAG-

SL task, participants balanced on their dominant limb a distance equal to half of their leg length away from the force plates. They were then instructed to hop forward, land on the same limb and subsequently perform a maximal countermovement hop off the same limb, reaching for the overhead target with the contralateral hand.

For the FRONT-DL task, participants began straddling a line placed a distance equal to one half of their leg length away from the lateral edge of the closest force plate. They then jumped laterally (toward the direction of the dominant limb), landing simultaneously with each foot on a separate force plate and performed a maximal countermovement jump, reaching for the target with both hands. The FRONT-SL task began with the participant balanced on their non-dominant limb behind the same line used for the FRONT-DL task. Participants then hopped laterally toward and landed on their dominant limb before performing an immediate maximal countermovement hop, reaching for the target with the contralateral hand.

Data Reduction. All biomechanical data were processed with Visual 3D (Version 5, C-Motion, Inc., Rockville, MD, USA) using custom MATLAB code (Version 8.0, The Mathworks, Natick, MA). Hip joint centers were calculated using the Bell Method (Bell et al., 1990), while the knee and ankle joint centers were defined as the centroid position of medial and lateral knee joint line and malleoli makers, respectively. Joint angle and moment data were reduced using low-pass, fourth-order Butterworth filters with a cutoff frequency of 12 Hz. Hip flexion, adduction, and internal rotation, and knee extension, adduction, and internal rotation were reduced as positive motions.

Biomechanical measures for hip flexion, adduction, internal rotation, and knee flexion, abduction, internal rotation and external rotation have all been theorized to influence high-risk movement patterns (Hashemi et al., 2011; Hewett et al., 2005; Shimokochi & Shultz, 2008), and were therefore the focus of this study. For each of these 7 motions, peak joint angles, total joint excursions (absolute value of the peak angle minus the angle at initial contact), and external joint moments (normalized to body mass and height) during the landing phase (period from initial contact to maximal descent of the body center of gravity) were extracted at each measurement time point for the first jump landing (prior to maximum countermovement jump or hop) of each trial. Delta scores were then computed (post-test – pre-test) to determine changes in each biomechanical measure over time. Ensemble curves of select variables were generated in MATLAB by normalizing each variable to the duration of ground contact, and were used to visually compare and interpret differences between pre- and post- test measures.

Training Protocol

The ACL injury prevention program developed by Labella et al (2011) was used in this study (Table 5.1). This program was chosen because of evidence that it successfully reduces the risk of ACL injury in female athletes, has been implemented in women's basketball and soccer players, and utilized a warm-up based training program (LaBella et al., 2011; J. B. Taylor, Waxman, et al., 2015). Although independent, isolated prevention training may more effectively reduce injury risk (Sugimoto, Myer, Foss, & Hewett, 2014), warm-up based programs are more popular and easier to implement over a large number of players and teams, improving recruitment and compliance for this study. Training sessions were performed prior to each team's practice at their own training facility and were all led by the same member of the research team, who provided real-time feedback with verbal cues to all participants, focusing mostly on soft landings and frontal plane knee control, as described in the original intervention (LaBella et al., 2011). Training sessions were held 2-3 times per week for 6 weeks, in accordance with each team's practice schedule, and lasted 20-25 minutes in duration. Typical warm-up based prevention programs are designed for an entire season, yet six weeks was chosen in this study to best align the basketball and soccer off-seasons as part of the larger study. This is common in ACL injury prevention, as other studies that have utilized warm-up based programs in female athletes have implemented a 5-6 week pre-season program followed by a weekly in-season maintenance program (Myklebust et al., 2003; Olsen et al., 2005). Additionally, past evidence supports the ability to observe neuromuscular adaptations within six weeks of the onset of training (Chappell & Limpisvasti, 2008; Chimera et al., 2004; Dawson & Herrington, 2015; Dempsey et al., 2009; Myer et al., 2005). Attendance was taken at each training session to record compliance, but no *a priori* compliance threshold was set for exclusion from the study prior to training to best replicate current clinical practice. Participants in the control group continued their normal sport training and competition, but were asked not to participate in any dedicated injury prevention training during the study.

Statistical Analysis

All statistical analyses were performed in SPSS, version 23 (IBM Corp, Armonk, New York), with statistical significance set *a priori* at α=.05 for all analyses. Independent t-tests were used to identify differences in age, height, mass, BMI and current training volume between the control and intervention groups. Then, 2 (group: intervention vs. control) x 4 (task: SAG-DL, SAG-SL, FRONT-DL, FRONT-SL) repeated measures MANOVAs containing the peak joint angle, total joint excursion, and peak moment for each selected motion were analyzed using pre-test values to determine if there were any biomechanical differences between groups at baseline. Six MANOVA models were analyzed: 1) hip flexion, 2) hip adduction, 3) hip internal rotation, 4) knee flexion, 5) knee abduction, 6) knee internal/external rotation. Any differences in baseline measurements were then controlled for in subsequent analyses.

All comparisons between pre- and post-tests were performed using the intention-to-treat principle and a last observation carried forward design (A. Herman et al., 2009; Portney & Watkins, 2009). Delta scores were used in subsequent 2 (group: intervention vs. control) x 4 (task: SAG-DL, SAG-SL, FRONT-DL, FRONT-SL) repeated measures MANOVA models to compare biomechanical improvements in response to the intervention across the four tasks. As before, each model contained the peak joint angle, total joint excursion, and peak moment for each task of the selected motion. Multivariate statistical significance was analyzed for the group main effect and group x task interaction using Wilk's Lambda. Follow-up post-hoc pairwise comparison using independent t-tests were performed to identify significant group main effects. Significant group x task interactions were followed with planned independent t-tests between intervention and control groups for each task, and paired t-tests of delta scores comparing the intervention group's delta scores of SAG-DL task to delta scores of the other three tasks. Cohen's *d* effect sizes and 95% confidence intervals (CI) were calculated for all biomechanical variables that exhibited statistically significant effects.

Results

A CONSORT flow diagram is presented in Figure 5.1 for the participants in the study that began in May 2015 and ended in October 2015 after the appropriate number of teams/participants were recruited, enrolled, and completed pre- and post-test data collection sessions. In the intervention group, two injuries unrelated to the training program occurred over the course of the study, including a concussion and undisclosed overuse foot injury. Two other participants were non-compliant and did not attend the post-testing session and one other participant was post-tested but her data was uninterpretable. In the control group, two participants did not return for post-testing sessions and one other's post-test data was also uninterpretable because of similar technical issues. Pre-test data was carried forward for each of the participants with no or uninterpretable post-test data (intervention, n=5; control, n=3). The attendance rate at training for the intervention group was 66.4±17.6%, averaging 1.7±0.5 training sessions per week.

At baseline, there were no significant differences in age (p=.34), height (p=.07), mass (p=.94), BMI (p=.26), current training volume (p=.72) (Table 5.2), or any lower extremity biomechanics measures between intervention and control groups (p>.05). Average pre-test, and delta scores for each dependent variable are reported by task in Table 5.3 and Table 5.4, respectively. Relative to the control group, there were no significant differences in hip flexion (λ=.94, p=.13), hip adduction (λ=.99, p=.10), hip internal rotation (λ=.98, p=.52), knee flexion (λ=.96, p=.26), knee abduction (λ=.99, p=.91) or knee internal/external rotation (λ=.91, p=.19) measures.

Additionally, no significant group x task interactions were identified in hip flexion (λ=.87, p=.20), hip adduction (λ=.87, p=.23), hip internal rotation (λ=.90, p=.47), knee flexion (λ=.89, p=.34), or knee internal/external rotation (λ=.78, p=.27) measures. A significant group x task interaction was identified in knee abduction (λ=.80, p=.02). Post-hoc pairwise comparisons showed no significant differences in knee abduction measures between intervention and control groups for any of the tasks (p>.05); however, paired t-tests revealed significant differences in knee abduction moments (KAM), such that participants in the intervention group showed larger improvements (decreases) in KAM during the SAG-DL than during the SAG-SL (p=.005; d=0.45, CI=0.04-0.85) task and also trended toward significance in the FRONT-SL (p=.07; d=0.25, CI=-0.16-0.65) task (Figure 5.2).

Discussion

Neuromuscular ACL injury prevention programs performed during a team's warm-up procedures are generally successful at reducing injury rates in female athletes that participate in multi-directional sports (J. B. Taylor, Waxman, et al., 2015); however, ACL injuries continue to occur at an alarming rate in these populations and are less successful in sports that require a strong frontal plane component (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007). Results from this study indicate that an established, successful warm-up based injury prevention program elicits no significant biomechanical adaptations after 6-weeks of training. These results were consistent across a variety of double- and single-leg multidirectional jump landing tasks, though there was some evidence of larger adaptations in knee abduction moments during SAG-DL than SAG-SL or FRONT-SL tasks. The lack of substantial biomechanical improvement is in concordance with numerous other studies that have investigated short duration warm-up based injury prevention programs (Grandstrand, Pfeiffer, Sabick, DeBeliso, & Shea, 2006; Zebis et al., 2015), leaving the mechanism by which these programs successfully reduce injury risk unanswered.

As previously stated, our findings are consistent with past literature that has reported minimal kinematic and kinetic changes during jump landings following a neuromuscular warm-up injury prevention program (Chappell & Limpisvasti, 2008; Grandstrand et al., 2006; Lim et al., 2009; Zebis et al., 2015). Both Chappell et al. (2008) and Lim et al.(2009) have reported mild increases of 2-5 degrees of knee flexion during double-leg sagittal plane jump landings tasks after 15-20 minute training sessions performed before athletic practices (~6 times per week). During a side-cut motion, Zebis et al. (2015) reported no kinematic or kinetic changes after 12 weeks of warm-up preventative training, though alterations in quadriceps and hamstring muscle activation were identified. Other studies have reported further kinematic changes, including increased hip abduction and decreased hip internal rotation, yet the training program was completed throughout an entire season, and analyses excluded participants with less than 80% compliance, potentially inflating the biomechanical changes seen during real-life application (Pollard et al., 2006). Our results are more indicative of true estimates of biomechanical adaptations, as we had no compliance thresholds and used an intention to treat with last observation carried forward model to provide a conservative estimate of change. In comparison to these data from warm-up prevention programs, other previous studies have reported considerable improvements in both knee flexion and knee abduction kinematic and kinetic measures after ACL injury prevention training with dedicated independent training sessions (60-90 minutes in duration) (Hewett et al., 1996; Lephart et al., 2005). This may suggest that current neuromuscular warm-up programs may not provide the appropriate volume or intensity to modify lower extremity biomechanics or that longer bouts of training (>6 weeks and >2-3 times per week) are necessary to observe changes in movement strategies. Multiple meta-analyses have reported that higher training durations may lead to greater success at reducing ACL injury rates (Gagnier et al., 2013; Sugimoto et al., 2014). Continued investigation attempting to understand the mechanism by which warm-up programs have improved ACL injury risk is warranted, considering their ease of implementation and relative popularity amongst coaches and athletes.

Based on the biomechanical adaptations observed with knee abduction moments, there was some evidence to suggest that biomechanical changes may not be equal across different tasks. Specifically, improvements in knee abduction moments were exhibited to a greater extent during the SAG-DL (17% decrease) than during the SAG-SL task (17% increase) and to a lesser extent, the FRONT-SL task (4% decrease). These differences may be important because a majority of ACL injuries occur during single-leg ground contact and most multi-directional sports incorporate large frontal plane demands. For example, time-motion analyses indicate that sports such as basketball and handball have large frontal plane demands, with basketball requiring higher frequencies of lateral movement than running or jumping (Matthew & Delextrat, 2009; Michalsik, Madsen, & Aagaard, 2014), potentially placing these athletes in more frequent injurious situations during frontal than sagittal plane activities. Changing the base of support from double-leg to single-leg, and altering the plane of movement have been reported to drastically alter the movement strategies needed to perform the task (Ford et al., 2006; Sinsurin et al., 2013a, 2013b; J. B. Taylor et al., 2016). Specifically, single-leg landings are performed with less flexion and higher joint moments at the hip and knee (J. B. Taylor et al., 2016). Additionally, frontal plane jump landings also elicit decreased amounts of hip and knee flexion angles and moments, along with greater knee abduction angles and moments (Sinsurin et al., 2013a; J. B. Taylor et al., 2016). Further, movement strategies used during sagittal plane tasks are unrelated to movement strategies elicited during frontal plane tasks (J. B. Taylor et al., 2016). With the potential that ACL injuries may occur more frequently during single-leg and laterally directed motions (Boden et al., 2009), the biomechanics associated with these activities deserve more attention and continued research.

Further exploration of the exercise prescription used in the training program may help to explain the lack of biomechanical improvements after 6 weeks of training. As a warm-up based intervention, the goal was to prepare athletes to play with non-fatiguing strength, plyometric and agility exercises. Thus, all exercises were performed with body weight resistance and minimal high-intensity activities. Results suggest that after 6 weeks of training, these types of programs may not supply the stimulus needed to promote neuromuscular or biomechanical adaptations that have been reported with isolated preventative training sessions with higher intensity exercises (Hewett et al., 1996). This is especially true of single-leg and frontal plane activities, as four of fifteen plyometric exercises were performed on a single-leg and only three of the twelve strengthening exercises (diagonal lunge, lateral lunge, side plank), three of fifteen plyometric exercises (lateral cone jumps, lateral bounding, diagonal bounding), and one of three agility exercises (lateral shuffling) required movement in the frontal plane in our study. Considering the specificity of exercise principle (Baechle & Earle, 2000), the large emphasis placed on double-leg and sagittal plane movements during the training program may also not provide the stimulus to produce biomechanical adaptations during single-leg and/or frontal plane movements. As such, there has been little evidence that the biomechanical adaptations observed after completing an ACL injury prevention program translate to other tasks. Brown et al. (2014) reported significant improvements during double-leg sagittal but not single-leg frontal plane landing tasks after completing a program that largely emphasized sagittal plane and double-leg strengthening and plyometric training exercises. Our results complement these findings and suggest that future ACL injury prevention programs geared towards multi-directional sport athletes may benefit from a larger emphasis on single-leg movements and activities outside of the sagittal plane.

Despite the lack of biomechanical adaptations experienced in our participants, the training program implemented in this study has reported excellent success in reducing ACL injury risk (LaBella et al., 2011). LaBella et al. (2011) reported a significant reduction in non-contact ACL injuries (injury rate ratio: 0.20, 95% CI: 0.04-0.95) in close to 1500 female high school basketball and soccer players over the course of training during one season; however, the neuromuscular adaptations that occur to reduce injury risk are still relatively unknown. Our study may have resulted in more meaningful biomechanical adaptations had our compliance rates equaled that of the original study (~80%), considering compliance has been directly related to injury risk reduction (Hagglund, Atroshi, Wagner, & Walden, 2013). However, increasing our compliance rate from ~60% to ~80% would have increased the volume of training, yet would still not have matched the original study, as those teams participated in preventative training for the duration of the competitive season. This may be important, because other studies utilizing neuromuscular warm-up routines as injury prevention measures have shown a trend of reducing injuries more toward the end than the beginning of the season (Gilchrist et al., 2008). Potentially, six weeks was not long enough to measure true biomechanical adaptations in our study. Other adaptations may have occurred, such as changes in strength or muscle activation, yet these outcome measures were not collected in this study. A recent meta-analysis investigated whether ACL injury prevention programs modify lower extremity biomechanics during cutting tasks, and reported no changes in lower extremity kinematics or kinetics, but observed changes in hamstring muscle activity after various training regimens (Pappas et al., 2015). However, many adolescent female athletes are not afforded the luxury of a six-week or longer pre-season in which to participate in an ACL injury prevention program. In many high school situations, the pre-season is limited to 3-4 weeks. Thus, identifying the extent to which biomechanics, strength, and muscle activation change and the timing that these changes occur after a warm-up based ACL injury prevention program will help clinicians better enhance implementation procedures.

This, and other ACL injury prevention programs may also benefit from the optimization of technique feedback. It is possible that different feedback strategies may have promoted greater biomechanical adaptations. Consistent with the original study, the trainer in our study provided individualized feedback to participants in the intervention group using terms such as “don’t let your knees cave inward” and “bend your knees”. These phrases place an intrinsic focus on the desired results, whereas promising evidence shows that use of cues and feedback with an external focus may enhance skill acquisition, retention, and allow for more efficient transfer of biomechanical changes to other sport activities (Benjaminse et al., 2015; Benjaminse, Welling, Otten, & Gokeler, 2014; Gokeler et al., 2013). In addition, the type of feedback may be important, as feedback related to kinetic variables has been shown to be more effective than kinematic feedback in reducing both knee abduction angles and moments (Ford, DiCesare, Myer, & Hewett, 2014). Future work identifying the most efficient modes of feedback, including internal vs. external focus, kinematic vs. kinetic data, and proximal vs. distal cues will help to continue optimizing ACL injury prevention programs.

Limitations

Although this study was performed as ACL injury prevention programs are typically implemented in clinical practice, the results of this study may be more a function of the compliance rates and volume of training versus the true effects of the exercise prescription. Thus, future studies may benefit from more standardized approaches, with strict compliance requirements. Additionally, although relatively minor, the training program used in this study did incorporate some frontal plane directed exercises, which may have minimized biomechanical adaptations between the two planes; however, the question still remains if the adaptations (once demonstrated) would be of similar magnitude across tasks. Lastly, none of the jump landing tasks used in this study to assess biomechanical adaptations after the prevention program have been validated as a tool to assess injury risk (Hewett et al., 2005). Although evidence indicates these tasks can be performed with good to excellent day to day reliability and consistency (J. B. Taylor et al., 2016), these tasks need prospective evaluation to establish their role in injury risk prediction.

Conclusion

No significant biomechanical changes were observed after a 6-week neuromuscular warm-up based ACL injury prevention program in female multi-directional sport athletes, which may suggest athletes need to participate in preventive training for longer than 6 weeks and more frequent than 2-3 times per week. Additionally, biomechanical adaptations that may occur in one task may not translate to other components of multi-directional sports. Considering the large single-leg and frontal plane demands of certain sports with high ACL injury rates (i.e. basketball), future exercise prescription and screening procedures may need to incorporate a larger emphasis on single-leg and frontal plane activities.

Tables and Figures

Table 5.1. Training Program Used in this Study (Originally Developed by LaBella et al, 2011)

WEEK 1	WEEK 2	WEEK 3-6
Jog	Jog	Jog
Dynamic Warm-Up*	Dynamic Warm-Up*	Dynamic Warm-Up*
	Strengthening	
Heel Raises[†]	Heel Raises[†]	Heel Raises[†]
Squats[†]	Squats[†]	Squats[†]
Plank/Side Plank[‡]	Plank/Side Plank[‡]	Plank/Side Plank[‡]
Push-ups[†]	Push-ups[†]	Push-ups[†]
Forward Lunge[†]	Lateral Lunge[†]	Lateral Lunge[†]
Supermans[†]	Diagonal Lunge[†]	Diagonal Lunge[†]
Swimmers[†]	Supermans[†]	Walking Lunge[†]
	Swimmers[†]	Supermans[†]
	Modified Supermans[†]	Swimmers[†]
		Modified Supermans[†]
	Plyometrics	
Ankle Bounces[‡]	Ankle Bounces[‡]	Ankle Bounces[‡]
Tuck Jumps[‡]	Tuck Jumps[‡]	Tuck Jumps[‡]
180 degree rotate[‡]	Squat Jumps[‡]	Squat Jumps[‡]
Squat Jump[‡]	Forward/Lateral Cone Jumps[‡]	Forward/Lateral Cone Jumps[‡]
DL Broad Jump for Distance[^]	Scissor Jumps[‡]	SL Hop, Hop, Stick[^]
Forward/Lateral Cone Jumps[‡]	Lateral Bounding[‡]	SL Jump for Distance[^]
SL Bound in Place[^]	SL Hop, Hop, Stick[^]	Jump into Bounding[‡]
	Broad Jump x3, Vertical Jump[^]	Diagonal Bounding[‡]
	Agility	
Shuttle Run[∞]	Shuttle Run[∞]	Shuttle Run[∞]
Diagonal Run[∞]	Diagonal Run[∞]	Diagonal Run[∞]
Lateral Shuffle[∫]	Lateral Shuffle[∫]	Lateral Shuffle[∫]

*dynamic warm-up included 50ft each of: jogging, skipping, carioca, side shuffle with arm swing, sprint at 75% maximum, high-knee skipping, high-knee carioca, sprint at 100% maximum, backward jog, bear crawl, butt kickers, backward jog half-length, turn and sprint, and diagonal skipping. Also 10 repetitions each of arm swings, trunk rotations, and leg swings

† activities performed for desired number of repetitions: week 1- 10 reps, week 2- 20 reps, week 3-6- 30 reps

‡ activities performed for desired amount of time: week 1- 10 seconds or reps, week 2- 20 seconds or reps, week 3-6- 30 seconds or reps

^ activities performed 5 times for double-leg (DL) and 5 times on each side for single-leg (SL) tasks

[∞] agility exercises performed for 50 feet, 10 repetitions

[∫] agility exercises performed for 15 feet, 10 repetitions

Table 5.2. Mean ± Standard Deviation Describing Intervention and Control Groups.

	Intervention (n=48)	**Control** (n=49)	**p-value**
Age	15.4 ± 1.0	15.7 ± 1.6	.34
Height (m)	1.65 ± 0.07	1.67 ± 0.06	.07
Mass (kg)	60.4 ± 11.3	60.2 ± 7.0	.94
BMI (m/kg^2)	22.1 ± 3.0	21.5 ± 2.1	.26
Training volume (Days/week)	4.2 ± 1.2	4.3 ±1.1	.72

Table 5.3. Means ± Standard Deviations for Kinematic Variables During the Jump Landing Tasks.

			SAG-DL		SAG-SL		FRONT-DL		FRONT-SL	
			Pre-	Delta	Pre-	Delta	Pre-	Delta	Pre-	Delta
Peak Angles (degrees)	Hip Flexion (+)	Int	61.6±8.0	-0.4±6.2	44.6±8.7	1.2±6.9	55.7±7.6	-1.4±10.6	47.3±7.5	-0.5±5.3
		Cont	64.7±8.4	-0.8±5.7	47.5±8.0	-0.9±5.4	57.5±10.3	-0.6±12.7	48.1±8.1	0.1±7.0
	Hip Adduction (+)	Int	0.6±3.9	0.004±4.1	9.3±4.8	1.4±4.0	-4.7±5.1	-0.3±4.9	3.0±6.5	-1.2±4.8
		Cont	1.5±5.6	0.3±3.3	10.0±4.2	-0.7±4.7	-3.6±6.8	-0.3±6.3	4.1±6.7	0.1±5.4
	Hip Internal Rotation (+)	Int	-1.9±8.1	3.3±8.1	-1.9±7.9	3.2±6.8	2.1±8.8	3.6±10.7	5.9±8.7	2.0±7.0
		Cont	-2.0±7.2	2.4±6.0	-2.6±6.8	1.9±5.1	2.7±6.8	3.6±8.4	3.1±7.7	2.2±5.8
	Knee Flexion (-)	Int	-80.8±8.6	-0.1±5.0	-55.5±7.0	0.3±4.5	-72.7±7.0	2.1±7.1	-59.0±6.2	1.0±4.5
		Cont	-83.4±8.5	1.2±4.8	-57.5±7.4	1.3±4.1	-73.4±8.0	0.5±8.5	-60.4±6.1	0.3±3.2
	Knee Abduction (-)	Int	-7.2±7.5	1.0±5.5	-4.3±5.9	0.4±3.8	-8.3±7.0	2.0±7.4	-5.8±5.9	1.6±4.4
		Cont	-8.1±4.9	1.0±3.7	-5.1±4.4	1.1±3.3	-7.0±5.2	0.2±5.5	-5.8±4.6	0.7±3.1
	Knee External Rotation (-)	Int	0.1±5.4	-1.4±5.2	-0.5±5.4	-0.7±5.7	-2.2±5.2	-1.6±7.7	-1.7±5.5	-2.9±6.2
		Cont	-1.3±6.0	-0.2±4.9	-1.5±5.1	-0.3±4.9	-3.9±6.6	0.9±7.2	-2.8±5.8	0.5±5.6
	Knee Internal Rotation (+)	Int	11.0±5.9	0.5±5.9	9.7±4.6	1.4±5.9	9.2±5.9	0.7±7.3	10.3±5.2	-0.3±5.9
		Cont	10.1±5.8	0.4±3.5	9.8±5.0	0.1±3.0	8.2±6.4	0.7±7.2	8.9±5.6	0.5±3.6
Angular Excursions (degrees)	Hip Flexion	Int	16.2±8.4	1.4±6.1	9.8±6.2	-0.4±3.8	22.5±11.2	0.07±12.8	15.4±9.3	-0.04±4.6
		Cont	17.7±10.2	-1.0±6.5	9.3±6.1	-1.4±5.4	23.4±12.3	-3.5±13.5	14.5±8.1	-1.5±4.9
	Hip Adduction	Int	3.3±3.1	-0.3±2.8	9.7±4.1	-0.1±3.1	8.3±4.9	-0.9±5.2	21.6±5.8	-0.6±3.7
		Cont	5.2±4.4	-0.7±2.4	10.9±4.7	-1.4±3.7	8.7±5.7	-0.4±6.5	23.0±5.7	-0.7±4.4
	Hip Internal Rotation	Int	6.6±5.5	4.3±9.7	6.9±4.2	3.3±5.6	7.8±5.3	2.3±9.0	6.6±5.1	2.2±5.1
		Cont	8.3±7.0	1.8±7.0	7.4±4.0	0.9±5.0	6.3±4.5	2.6±5.9	5.2±4.0	2.1±4.4
	Knee Flexion	Int	59.1±10.6	3.1±8.2	39.9±8.2	0.3±5.3	47.3±12.0	-1.7±14.3	37.8±8.9	-0.7±5.0
		Cont	61.6±9.8	-1.5±7.4	40.4±7.4	-1.9±5.0	45.3±12.7	-2.0±12.9	36.1±8.0	-1.1±4.9
	Knee Abduction	Int	7.1±4.9	-1.3±4.4	4.1±3.7	-0.8±2.8	5.0±4.0	-1.2±4.4	4.5±3.2	-0.9±3.2
		Cont	7.5±4.4	-1.4±3.0	4.3±3.2	-1.0±2.1	4.3±3.8	-0.9±4.2	5,4±2.9	-0.9±2.4
	Knee External Rotation	Int	2.8±3.8	2.2±6.2	3.1±2.7	2.7±5.2	1.9±2.5	0.1±4.4	5.0±4.1	1.5±4.7
		Cont	3.4±4.9	1.7±5.3	3.8±3.6	0.9±4.9	1.5±2.3	0.4±3.6	4.4±4.3	0.6±4.3
	Knee Internal Rotation	Int	8.2±5.7	-0.3±5.1	7.1±4.4	-0.6±4.3	9.6±4.8	2.4±5.5	6.9±5.2	1.1±5.0
		Cont	8.1±5.3	-0.9±4.7	7.5±4.2	-0.5±4.4	10.7±4.2	-0.5±5.8	7.3±4.2	-0.7±3.0

Table 5.4. Means ± Standard Deviations for Kinetic Variables During the Jump Landing Tasks.

			SAG-DL		**SAG-SL**		**FRONT-DL**		**FRONT-SL**	
			Pre-	Delta	Pre-	Delta	Pre-	Delta	Pre-	Delta
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.20±0.28	0.07±0.26	1.68±0.36	0.22±0.38	1.12±0.29	0.11±0.29	1.32±0.30	0.06±0.25
		Cont	1.24±0.30	0.09±0.25	1.71±0.39	0.10±0.31	1.15±0.32	0.10±0.36	1.35±0.33	0.07±0.24
	Hip Adduction (+)	Int	0.15±0.13	0.02±0.13	0.99±0.23	0.02±0.20	0.08±0.16	0.01±0.21	0.65±0.20	-0.01±0.19
		Cont	0.18±0.17	0.02±0.12	1.02±0.20	-0.03±0.17	0.07±0.19	0.04±0.20	0.71±0.23	0.01±0.15
	Hip Internal Rotation (+)	Int	0.32±0.11	-0.02±0.09	0.39±0.12	0.02±0.11	0.36±0.13	-0.003±0.14	0.43±0.14	-0.02±0.12
		Cont	0.32±0.09	-0.003±0.07	0.42±0.12	0.01±0.10	0.34±0.11	0.02±0.11	0.40±0.14	0.01±0.10
	Knee Flexion (-)	Int	-1.23±0.21	0.02±0.20	-1.58±0.28	0.05±0.21	-1.26±0.41	0.05±0.50	-1.29±0.23	0.07±0.22
		Cont	-1.28±0.23	-0.01±0.20	-1.66±0.28	0.03±0.20	-1.24±0.31	-0.02±-0.33	-1.33±0.25	0.03±0.20
	Knee Abduction (-)	Int	-0.24±0.14	0.04±0.11	-0.12±0.16	-0.02±0.13	-0.32±0.22	0.05±0.26	-0.26±0.13	0.01±0.11
		Cont	-0.24±0.11	0.04±0.10	-0.10±0.13	0.003±0.10	-0.27±0.15	-0.0003±0.14	-0.22±0.09	0.01±0.08
	Knee External Rotation (-)	Int	-0.04±0.05	-0.004±0.03	-0.37±0.11	0.03±0.09	-0.05±0.07	0.002±0.09	-0.26±0.08	-0.01±0.09
		Cont	-0.04±0.06	0.001±0.03	-0.39±0.07	0.01±0.07	-0.04±0.07	-0.006±0.09	-0.29±0.10	0.01±0.07
	Knee Internal Rotation (+)	Int	0.13±0.07	-0.01±0.05	-0.003±0.03	0.01±0.03	0.15±0.08	-0.01±0.11	0.08±0.06	-0.001±0.04
		Cont	0.13±0.07	-0.004±0.05	-0.01±0.03	0.002±0.03	0.16±0.08	0.01±0.09	0.06±0.05	-0.003±0.03

Figure 5.1. CONSORT Flow Diagram Representing the Flow of Participants in this Study.

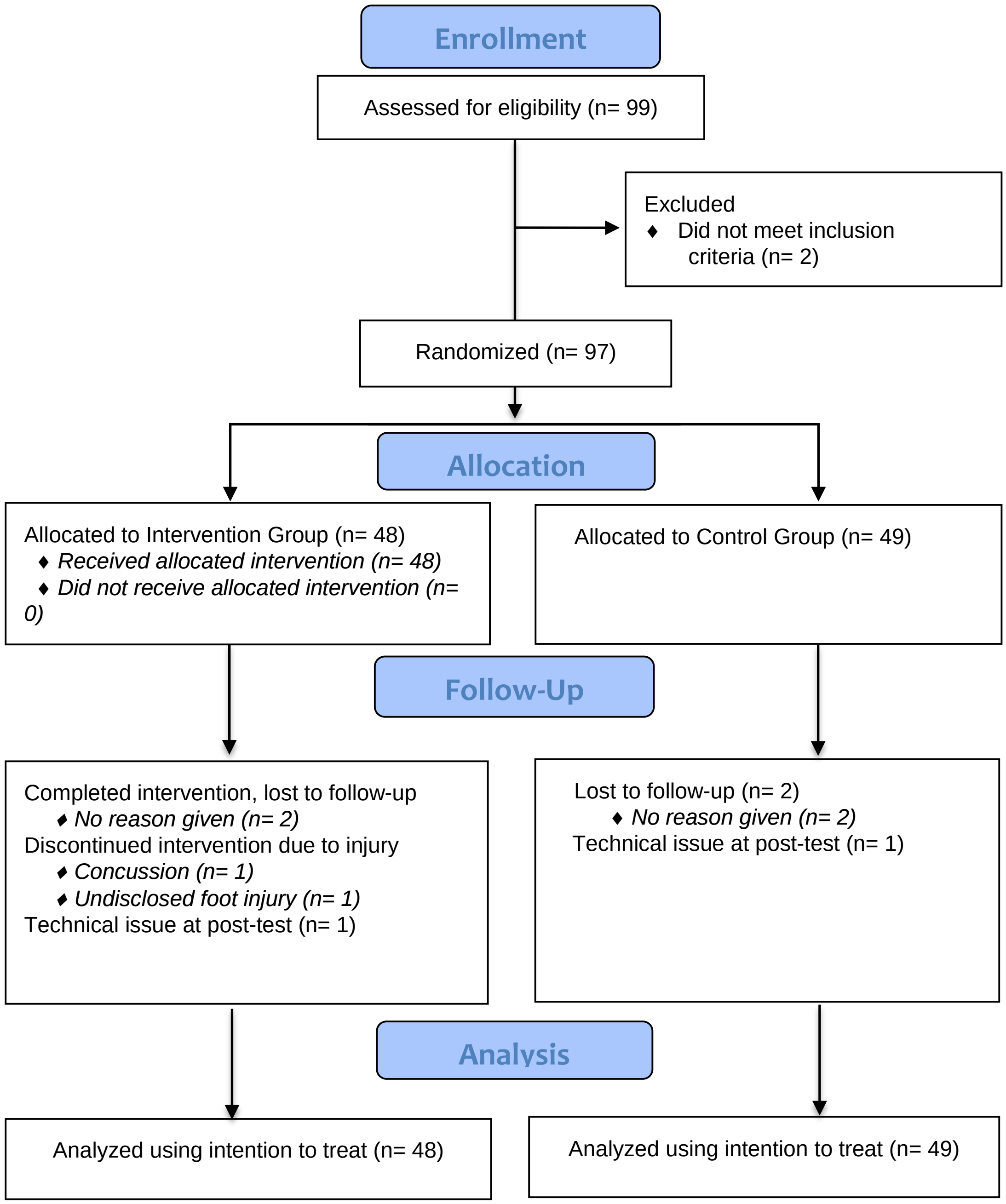
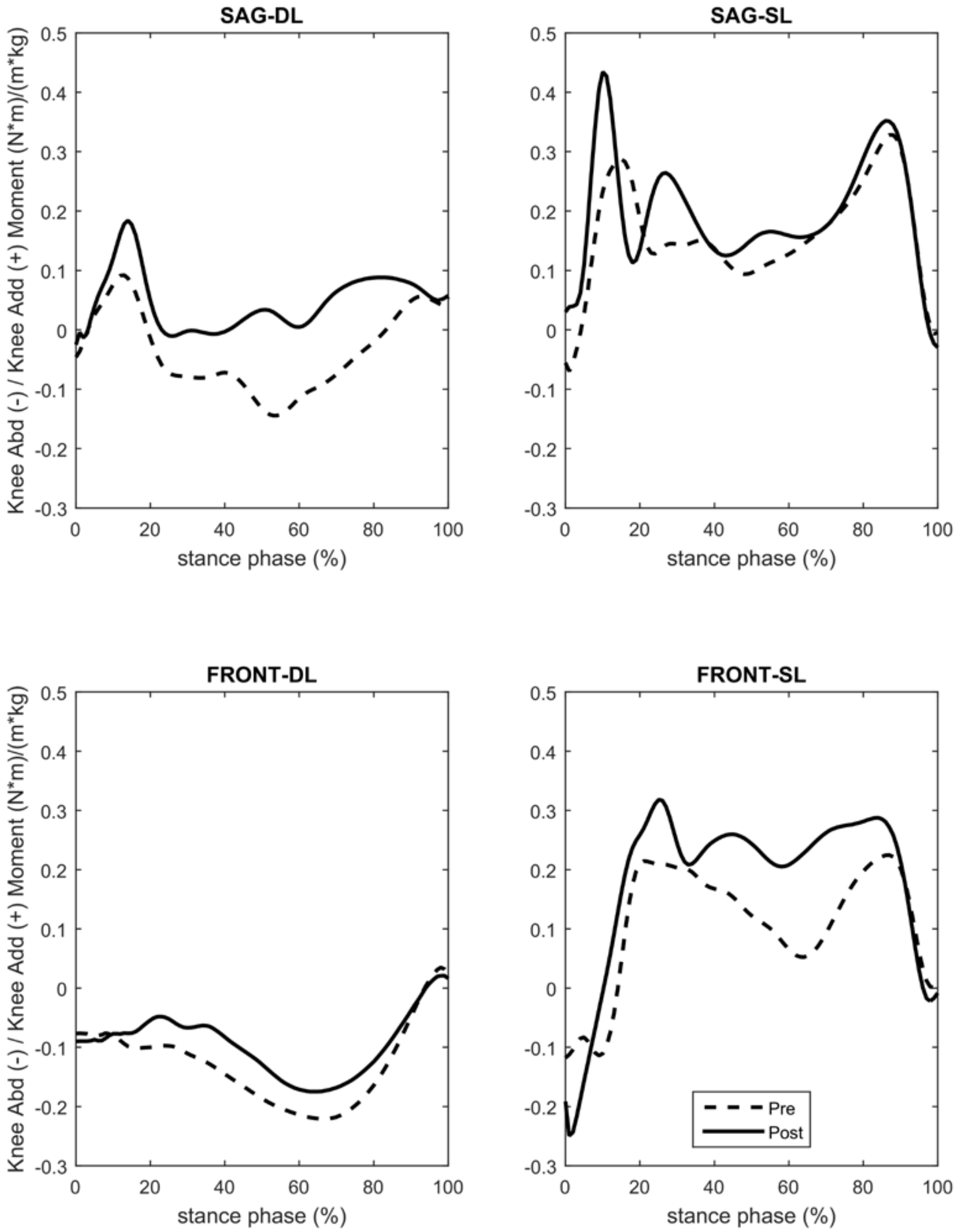


Figure 5.2. Ensemble Curves Showing Pre- and Post-test Knee Abduction Moments in the Intervention Group for All Tasks.



CHAPTER VI

MANUSCRIPT III

Title

Sport-specific biomechanical responses to an ACL injury prevention program: A randomized controlled trial

Abstract

Context

Despite similar incidence rates, anterior cruciate ligament injury prevention programs (ACL-IPP) are less successful at reducing injury rates in women's basketball than soccer.

Objective

To compare the extent to which an ACL-IPP differentially modifies lower extremity biomechanics in female basketball and soccer players during jump landing activities.

Design

Cohort study.

Setting

Biomechanics research laboratory, field-/court-based training program

Patients or Other Participants

A total of 87 competitive female basketball and soccer players that competed at the middle- or high-school level were cluster randomized into intervention (basketball: n=20; soccer: n=18) and control groups (basketball: n=23; soccer: n=26).

Intervention(s)

An established warm-up based ACL-IPP was administered for six weeks. Three-dimensional biomechanical analyses of a drop vertical jump (DVJ), double- (SAG-DL) and single-leg (SAG-SL) sagittal, and double- (FRONT-DL) and single-leg (FRONT-SL) frontal plane jump landing tasks were tested before and after the intervention.

Main Outcomes Measures

Using an intention to treat analysis, peak angles, excursions, and normalized joint moments were analyzed for sport differences using two-way MANCOVAs of post-tests scores while controlling for pre-test scores. Significant (α=.05) group x sport interactions were followed with planned pairwise comparisons using univariate ANCOVAs.

Results

No significant interactions were identified for the DVJ, SAG-DL, or FRONT-DL (p>.05). A significant interaction was identified for knee abduction during the SAG-SL (p=.01), such that the basketball intervention group exhibited increased peak angles (p=.004) and excursions (p=.003) compared to the basketball control group (p=.01) and soccer intervention group (p=.01). During the FRONT-SL task, a significant interaction was identified for knee flexion (p=.02), such that the basketball intervention group exhibited greater knee flexion excursion after training than the control group (p=.01), but not the soccer intervention group (p=.11).

Conclusion

Women's basketball and soccer players largely exhibit similar biomechanical adaptations to ACL-IPP after 6-weeks of training.

Key Words

ACL, injury prevention, biomechanics, basketball

Introduction

Anterior cruciate ligament (ACL) injury prevention programs have been successful at decreasing non-contact injury rates in adolescent female athletes (J. B. Taylor, Waxman, et al., 2015), reducing injury rates up to 88% in some studies (Mandelbaum et al., 2005). These prevention programs typically utilize a mixture of strength, plyometric, agility and balance training to improve neuromuscular control and movement strategies of the lower extremities (J. B. Taylor, Waxman, et al., 2015). Specifically, ACL injury prevention programs attempt to modify high-risk biomechanical movement patterns that may place an athlete at risk for ACL injury, including stiff-legged landings and dynamic lower extremity valgus (Boden et al., 2009; Hewett et al., 2005; Hewett et al., 2009; Krosshaug et al., 2007).

To date, ACL injury prevention programs have not been equally successful in all women's sports. Specifically, a significantly higher reduction of ACL injuries has been reported in women's soccer than women's basketball (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007). This is concerning, because at the youth and high school level, more female athletes participate in basketball than any other sport in the United States (Ackerman, 2013; National Federation of State High School Associations, 2012). Additionally, women's collegiate basketball players suffer non-contact ACL injuries at a higher rate than women's soccer players (Agel et al., 2005). Further, concomitant injuries resulting from ACL injury, such as meniscal and articular cartilage damage, are significantly more prevalent in women's basketball than other sports (Granan et al., 2013). This is problematic because individuals with a concomitant meniscal tear have a 21-48% risk of developing knee osteoarthritis 10 years after ACL injury, compared to a 0-13% risk in those without additional damage (Oiestad et al., 2009). Considering the rate and severity of ACL injuries in women's basketball and the long-term joint health problems associated with these injuries, further research is needed to understand the lack of effectiveness of ACL prevention programs in women's basketball players.

Potential factors that may explain the lack of efficacy of these programs in women's basketball versus soccer may include sport-specific differences in the mechanisms of ACL injury, functional demands of the sport, and anthropometric, neuromuscular and biomechanical characteristics of the athletes. In women's basketball, 60-86% of non-contact ACL injuries occur as a result of jump landings, compared to a much smaller percentage (0-25%) in soccer (Krosshaug et al., 2007; Piasecki et al., 2003). This may be influenced by sport-specific demands, as soccer players perform 50-70% less jumping activities during competition than basketball players (Matthew & Delextrat, 2009; Nedelec et al., 2014). Soccer players also perform considerably less lateral movements than basketball players, who perform more frontal than sagittal plane movements during game competition (Bloomfield et al., 2007; Matthew & Delextrat, 2009). Anthropometrically, women's basketball players are also taller, heavier and have larger body mass indices (BMI) than soccer players (Stanforth et al., 2013). This may directly influence neuromuscular control or biomechanical movement strategies, where basketball players typically display higher total forces during jumping tasks, yet lower forces during cutting tasks than soccer players (Cowley et al., 2006). Further, basketball players exhibit greater levels of lower extremity valgus during single-leg landings than soccer players (A. Munro et al., 2012), ultimately suggesting that basketball players appear to be at higher risk of ACL injury during jump landing activities.

Based on these differences, the lack of effectiveness of ACL injury prevention programs in women's basketball may result from one of two possible scenarios: either the exercise prescription is not appropriately designed to influence biomechanics for the unique high-risk movement demands of women's basketball (e.g. not sufficient emphasis in training frontal plane movements), or that women's basketball players are not as responsive to the same training stimulus as soccer athletes. To that end, previous evidence indicates that basketball and soccer players have distinct biomechanical and neuromuscular profiles, which become more prevalent as landings increase in complexity and simulate the single-leg and frontal plane demands of basketball (J.B. Taylor et al., 2016). However, the extent to which these athletes exhibit differential adaptations or whether responses to current ACL injury prevention programs differ during various jump landing tasks has not been studied. The purpose of this study was to examine the extent to which an established prevention program differentially modifies jump landing biomechanics in female soccer and basketball players during a variety of double- and single-leg sagittal and frontal plane jump landing tasks. Although there is evidence indicating that athletes exhibit unique neuromechanical adaptations to sport-specific training (Izquierdo et al., 2002), there is no evidence to suggest that athletes of different sports respond uniquely to the same training stimulus. Therefore, we hypothesized that all athletes, regardless of sport, would exhibit similar responses to the same training stimulus, ultimately leading to no appreciable differences in biomechanical adaptations between basketball and soccer players after training during any jump landing task.

Methods

Participants

Participants were recruited from teams of three local competitive basketball and soccer clubs. Interested participants were included in the study if they: 1) were 13-19 years old, 2) participated in middle or high school level competitive women's basketball or soccer, 3) were cleared to participate in unrestricted sport activity, and 4) had no lower extremity injury at time of testing. Participants were excluded if they reported a previous lower extremity surgery within the past 6 months or had been previously diagnosed with a vestibular, balance, or cardiac disorder. All participants provided written informed parental consent and participant assent as approved by the Institutional Review Boards of the lead author's institutions. After the initial testing session, if participants could not commit to completing the study in entirety (6-week intervention with pre- and post-tests), they were excluded from further testing and analysis.

An *a priori* power analysis was performed to determine the appropriate sample size for the study (G*Power, version 3.1.2), which deemed 80 participants (20 per group) adequate to achieve 80% power at a statistical significance criterion of 0.05 with a moderate effect size (0.38), and 25% drop out rate. Ninety-nine participants were initially enrolled in the study, and 97 were eligible for the randomized controlled trial. Participants were cluster randomized by team using an online random sequence generator into four parallel groups (basketball intervention, basketball control, soccer intervention, and soccer control). Group membership was kept in a concealed envelope and participants were informed of their group membership after their entire team completed the first testing session. Random allocation was performed by one member of the research team. All testing and training was performed by another investigator, which allowed blinded testing during the pre-, but not post-testing session.

Data Collection

Participants completed identical testing sessions at two time points (pre- and post-test) in a biomechanics laboratory setting. Participants in the intervention group were tested within two weeks prior to the scheduled onset of the training program and retested between 2-10 days after the completion of the last training session. Testing sessions for the control group were scheduled approximately 8-weeks apart. Each athlete completed an electronic questionnaire (REDCap™ software, Version 4.14) to identify the current training volume in their primary sport.

Limb Dominance. Analyses was performed on each athlete's dominant limb. Because the definition of limb dominance may differ between basketball and soccer players (i.e. jumping vs. kicking limb), limb dominance was defined based on participant performance during a triple hop for distance test (Hamilton et al., 2008). Participants performed 1-3 practice trials, and then three trials on each limb, with the order counterbalanced for each subject. Instructions were given to perform three consecutive maximal forward hops for distance on the same limb without hesitation. Distance was measured from the starting line to the point of toe contact upon completing the third hop utilizing a standard cloth tape measure affixed to the ground. Trials were repeated if the participant lost balance, contacted the ground with their opposite limb, or hesitated between hops. The limb which produced the single longest jump distance was subsequently defined as the dominant limb.

Instrumentation. All participants donned standardized, laboratory-provided footwear (adidas® adipure Trainer 360, Beaverton, OR) to control for the effect of footwear on biomechanical landing patterns. Then, as previously published, each subject was instrumented for three-dimensional biomechanical analysis (J. B. Taylor et al., 2016) with 43 retroreflective markers on their trunk and bilateral upper and lower extremities. A static trial was collected to determine each subject's neutral alignment and anatomically define each body segment, by which subsequent biomechanical measures were referenced. Three-dimensional motion data were collected with Cortex software (version 5, Motion Analysis Corporation, Santa Rosa, CA, USA) using a 14-camera system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA, USA) that sampled at 200 Hz. Kinetic data was sampled at 1200 Hz, collected by dual, in-ground, multi-axis force plates (AMTI, Watertown, MA, USA), such that each force plate collected data from a single leg.

Procedures. A hanging target was placed over the force plates at a height equal to the participants maximal vertical jump reach, as determined during 3-5 repetitions of a standing countermovement jump to ensure consistent, maximal effort. With the overhead target in place, participants completed three trials of five different landing tasks that were all followed by an immediate maximum countermovement jump or hop: 1) drop vertical jump (DVJ), 2) double-leg forward jump in the sagittal plane (SAG-DL), 3) single-leg forward hop in the sagittal plane (SAG-SL), 4) double-leg lateral jump in the frontal plane (FRONT-DL), and 5) single-leg lateral hop in the frontal plane (FRONT-SL) (J. B. Taylor et al., 2016). All tasks have established good to excellent day-to-day reliability and performance consistency (J. B. Taylor et al., 2016), and were selected to comprehensively simulate the multi-directional sport demands of basketball players.

A standard DVJ was performed using a 31-cm box. Participants were instructed to stand on top of the box with their feet spaced 35-cm apart and drop straight down, leaving the box and landing on the ground with both feet at the same time. Immediately upon landing, participants performed a maximum countermovement jump while reaching for the overhead target with both hands. The SAG-DL was performed with participants positioned a distance equal to their leg length (greater trochanter to lateral malleolus) away from the front edge of the force plates. They were instructed to jump forward, land simultaneously with both feet and immediately perform a maximal countermovement jump, reaching for the overhead target with both hands. For the SAG-SL, participants balanced on their dominant limb a distance equal to half of their leg length away from the force plates. They were then instructed to hop forward, land on the same limb and subsequently perform a maximal countermovement hop off the dominant limb, attempting to reach the overhead target with the contralateral hand.

For the FRONT-DL tasks, participants were positioned straddling a line placed a distance equal to one-half of their leg length away from the lateral edge of the nearest force plate. Participants then jumped laterally, landing with their feet facing forward and each foot on a separate force plate. Similar to the other tasks, participants were instructed to perform a maximal countermovement jump immediately upon landing, while reaching for the target with both hands. The FRONT-SL task began with participants standing on their non-dominant limb behind the same line used during the FRONT-DL task. Participants then hopped laterally toward their dominant limb (36 cm plus one-half of leg length away), and immediately performed a maximal countermovement hop, reaching toward the target with the contralateral arm. The first landing (prior to the maximal countermovement jump/hop) was used for analysis in all tasks.

Data Processing

Biomechanical data were processed in Visual3D (Version 5, C-Motion, Inc., Rockville, MD, USA) with custom MATLAB (Version 8.0, The Mathworks, Natick, MA) code. Joint angle and moment data were subjected to a low-pass fourth-order Butterworth filter with a cutoff frequency of 12 Hz. Hip flexion, adduction, and internal rotation and knee extension, adduction, and internal rotation were reduced as positive motions.

All biomechanical variables were analyzed during the landing phase, defined as the period from initial contact (first point that GRF surpasses 10N) to maximal descent of the center of gravity. Kinematic variables of interest were peak angles and excursion values for hip flexion, adduction and internal rotation, and knee flexion, abduction, internal rotation and external rotation. Joint excursions were calculated as the absolute value of the difference between the peak angle and angle at initial contact. Kinetic variables included peak hip flexion, adduction and internal rotation, and knee flexion, abduction, internal rotation and external rotation external joint moments during the landing phase. All moments were normalized to the subjects' height and mass to allow for more accurate comparisons between groups of athletes. These variables were selected based on collective thought that they may either influence dynamic valgus collapse or promote stiff-legged landings, theorized as the predominant mechanisms of ACL injury in female athletes (Hashemi et al., 2011; Quatman & Hewett, 2009; Schmitz et al., 2009). Trials were excluded if the participant did not land on the intended force plate or if tracking markers were covered and unidentifiable during movements, which accounted for less than 5% of trials in this study. Means of all successful trials for each task were calculated and used in statistical analyses. Ensemble curves of select biomechanical variables were generated in MATLAB by normalizing each variable to the duration of the landing phase to allow for visual comparisons between basketball and soccer players.

Training Protocol

An established 20-25 minute neuromuscular warm-up program, previously published by LaBella et al. (2011) was used as the ACL injury prevention program in this study. This program was chosen because of evidence that it successfully reduces the risk of ACL injury in female athletes, is the most recently reported and most effective study in women's basketball players, and utilized a warm-up based training program to help with coach and participant recruitment (LaBella et al., 2011; J. B. Taylor, Waxman, et al., 2015). The program was performed for 6-weeks and implemented at the beginning of every intervention team's scheduled practice session by the same member of the research team. Six weeks was chosen because it best aligned with teams' offseason schedules and was consistent with the duration of training used in other ACL injury prevention studies (Myklebust et al., 2003; Olsen et al., 2005). Additionally, past evidence supports the ability to observe neuromuscular adaptations within six weeks of the onset of training (Chappell & Limpisvasti, 2008; Chimera et al., 2004; Dawson & Herrington, 2015; Dempsey et al., 2009; Myer et al., 2005). Attendance was taken at each training session and participants were asked to provide a reason for missing training to better understand compliance issues.

The progression of exercises performed throughout the program is found in Table 6.1. Athletes were given real-time verbal feedback with cues such as "land softly" and "keep your knees over your toes" during all exercise sessions to focus on limiting lower extremity valgus and promoting greater levels of knee and hip flexion, as described in the original intervention (LaBella et al., 2011). Members of the control group were instructed to continue with normal basketball and soccer tactical/skill training, refraining from participation in any dedicated injury prevention, strength, or plyometric training programs.

Statistical Analyses

All statistical analyses were performed in SPSS, version 23 (IBM Corp, Armonk, New York), using measures from each athlete's dominant leg, with statistical significance set a priori at α=.05 for all analyses. All comparisons between pre- and post-tests were performed using the intention-to-treat principle and a last observation carried forward design (A. Herman et al., 2009; Portney & Watkins, 2009).

Basketball and soccer players have been reported to exhibit distinct biomechanical profiles (Cowley et al., 2006; A. Munro et al., 2012). Thus, to account for these differences and identify sport-specific responses to the training program, 2 (group) x 2 (sport) MANCOVA models of post-test scores were performed while covarying for pre-test scores (Rausch et al., 2003). For each jump landing task, six separate MANCOVA models were established, such that all biomechanical variables (peak angle, excursion, peak joint moment) associated with each joint motion were included in one model: 1) hip flexion, 2) hip adduction, 3) hip internal rotation, 4) knee flexion, 5) knee abduction, and 6) knee internal and external rotation. The sport x group interaction was analyzed using Wilk's Lambda, and statistically significant interactions were followed with planned post-hoc comparisons using univariate ANCOVAs. Specifically, while controlling for pre-test scores, post-test scores of the following cohorts were compared 1) basketball intervention and control group, 2) soccer intervention and control group, and 3) basketball and soccer intervention groups. Effect sizes (ES), in the form of partial eta-squared values were calculated for all biomechanical variables that exhibited statistically significant effects.

Additionally, independent t-tests confirmed that soccer players (mean= 11.9±2.1 sessions) in the training group participated in significantly more training sessions than basketball players (mean= 8.1±2.7 sessions, p<.001). Thus, similar ANCOVA models were repeated for all significant interactions between the intervention groups by controlling for both pre-test values and number of training sessions attended to analyze whether any identified sport-specific responses were due to more than the volume of training.

Results

Recruitment and data collection for the study began in May, 2015 and ended in October, 2015 once the prerequisite number of participants were enrolled and completed their post-testing session. A CONSORT flow diagram is presented in Figure 6.1. Of the 97 participants initially eligible for the study, 10 participants were excluded from these analyses because they participated in both competitive basketball and soccer during the previous academic year, leaving 87 total participants for the study (Table 6.2). In the intervention group, two injuries unrelated to the training program occurred over the course of the study, including a concussion and undisclosed overuse foot injury (2 soccer). Two participants were non-compliant (2 basketball) and did not attend the post-testing session and one other participant was post-tested but their data was uninterpretable due to technical difficulties. In the control group, two participants did not return for post-testing sessions (1 basketball, 1 soccer) and one other’s post test data was also unable to be interpreted for similar technical issues (1 soccer). Thus, pre-test data was carried forward for 5 and 3 participants in the intervention and control group, respectively. Overall compliance for the intervention group was 66.4±17.6% with no significant difference between basketball (68.2±20.9%) and soccer (66.0±11.9%, p=.68) players.

Pre-test and post-test scores for each sport are shown in Tables 6.3, 6.4, 6.5, 6.6, and 6.7 for all jump landing tasks. There were no significant group x sport interactions for the DVJ, SAG-DL, or FRONT-DL tasks (p>.05). A significant interaction was identified during the SAG-SL task for knee abduction (λ=.86, p=.01, ES=0.14), and the FRONT-SL task for knee flexion (λ=.88 p=.02, ES=0.12). For SAG-SL, the basketball intervention group had relatively greater increases in peak knee abduction angles (p=.004, ES=0.22) and excursions (p=.003, ES=0.22) compared to the basketball control group and the soccer intervention group (peak angle p=.01, ES=0.15; excursion p=.01, ES=0.17) (Figure 6.2). After controlling for the volume of training, the findings remained significant for peak knee abduction angles (p=.02, ES=0.14) and excursions (p=.02, ES=0.13). There were no differences between soccer intervention and control groups for peak abduction angles (p=.07) or excursions (p=.11). During the FRONT-SL task, the basketball intervention group showed a greater increase in knee flexion excursion compared to the control group (p=.01, ES=0.18); however, no significant differences were identified in knee flexion excursion between soccer groups (p=.54), or between the basketball and soccer intervention groups (p=.11) (Figure 6.2).

Discussion

To date, ACL injury prevention programs have conventionally been designed to target known and theorized risk factors for ACL injury, such as hamstring weakness, dynamic lower extremity valgus, and stiff-legged landings (Hashemi et al., 2011; Hewett et al., 2005; Myer et al., 2009; Shimokochi & Shultz, 2008). These “one size fits all” programs have been standardly implemented across athletes, regardless of sport-specific differences in activity demands or biomechanical profiles. Although these programs are successful at reducing overall injury rates (J. B. Taylor, Waxman, et al., 2015), they are far less successful in women’s basketball than soccer players (Michaelidis & Koumantakis, 2013; Prodromos et al., 2007). We had theorized that the discrepancy in success rates may be because ACL injury prevention programs are either not designed appropriately for women’s basketball players, or that women’s basketball players are not as responsive to the same training stimulus as soccer players. Our results implicate the former, because while basketball and soccer players exhibit distinct changes in a limited number of biomechanical variables (knee abduction angles and excursion during the SAG-SL task, and knee flexion excursion during the FRONT-SL task), effect sizes were relatively small and the athletes overwhelmingly displayed similar adaptations to the program across a variety of jump landing tasks. Somewhat unexpected, neither basketball nor soccer players exhibited appreciable biomechanical adaptations after the training program, which may suggest that the training stimulus lacked in duration, intensity, and/or effective exercise prescription.

Considering prior published reports of this intervention program successfully reducing ACL injury rates in a population of high school athletes (LaBella et al., 2011), we expected to observe substantially greater biomechanical adaptations after training. The lack of observed changes in our study may be attributed to an overall lack of training volume, as the program was only performed for 6 weeks, compared to an entire athletic season during which these programs are typically prescribed (and by which injury risk was determined in prior studies). However, past evidence indicates that 6-weeks of neuromuscular training can successfully induce biomechanical changes when performed 2-6 times per week (Chappell & Limpisvasti, 2008; Chimera et al., 2004; Dawson & Herrington, 2015; Dempsey et al., 2009; Myer et al., 2005). The frequency and periodization of the program also differed from the original study. Our study implemented the program during teams' offseason training, where the frequency of training (2-3x week) was considerably different than daily in-season training. Although overall compliance rates were relatively high in our study compared to others and were similar between sports, participants only received training an average of 10.1 times over the course of training. Despite the relative lack of volume, our results are consistent with previous literature that reports 15-25 minute warm-up based prevention programs elicit relatively less substantial biomechanical changes compared to isolated prevention training of larger durations (60-90 minutes per session) (Chappell & Limpisvasti, 2008; Hewett et al., 1996; Lephart et al., 2005; Zebis et al., 2015). While it is possible that 2-3 times per week for 6 weeks was an inadequate volume of training to elicit biomechanical adaptations, adolescent basketball and soccer teams rarely have greater than six weeks to devote to injury prevention programs prior to the start of competition. Thus, a more rigorous program may be needed during the pre- and off-seasons to elicit biomechanical changes in these athletes.

Although more intensive training may promote greater biomechanical changes, our results suggest that basketball and soccer players showed largely similar responses after training. Thus, if these athletes respond similarly to the same program, yet ACL injury prevention programs are not as successful in women's basketball players, future programs may need to be designed more specifically for the functional demands of the sport. Basketball has a large vertical component, requiring significantly more jumps and landings than soccer (Ben Abdelkrim et al., 2007; Matthew & Delextrat, 2009; Nedelec et al., 2014). Additionally, basketball players frequently move in the frontal plane while lateral shuffling, pivoting and jumping (Matthew & Delextrat, 2009), whereas soccer players spend more time in the sagittal plane, utilizing frequent cutting at shallower angles to change direction (Bloomfield et al., 2007). These variations in demands place athletes in distinct injurious situations, which may ultimately explain sport-specific differences in the mechanisms of ACL injury, which should be considered in future program development. Specifically, basketball players are more often injured during jumping and landing (Piasecki et al., 2003), while soccer players are typically injured during cutting maneuvers (Faude et al., 2005). While the training program used in our study did incorporate some frontal plane (e.g. lateral lunges, lateral bounding) and single-leg (e.g. single-leg bounding) exercises, a much larger emphasis was placed on double-leg movements in the sagittal plane.

The mechanism of injury may also be influenced by the size of the playing field and physicality of the game. At the international-professional level, a basketball court measures $420m^2$ (28m x 15m) with 10 players, compared to a soccer field of $7350m^2$ (105m x 70m) with 22 players. When accounting for the amount of playing surface per player, basketball athletes ($43.7m^2$) have a considerably lower surface area to player ratio than soccer players ($334.1m^2$), which may lead to more physical interactions and less space for competitors to maneuver. Krosshaug et al. (2007) reported that at least half of all non-contact ACL injuries were preceded by a slight contact or perturbation. Thus, core strength and stability may be a necessary component of preventive training to withstand perturbations and maintain biomechanical control of the center of mass and lower extremities. While the program tested in our study did incorporate some core training, (e.g. planks, supermans), these exercises were performed in relatively low volume and in non-functional prone or side-lying positions as opposed to more upright, closed chain postures (Ford et al., 2015; Myer, Brent, Ford, & Hewett, 2008). Future prevention programs in basketball players may need to incorporate higher volumes of frontal plane activities, single-leg landings, and reactive training to perturbations to account for the high-risk situations in basketball. However, more work is needed to fully elucidate why current programs are not successful in this population.

In addition to sport-specific functional demands, future ACL injury prevention programs may also need to account for the distinct biomechanical and neuromuscular profiles of women's basketball players. Models of injury prevention propose that preventive programs should be designed around the risk factors for that specific injury (van Mechelen et al., 1992). Although no basketball-specific ACL risk factor studies have been performed, previous evidence indicates that basketball players may possess less protective movement strategies, including stiffer landings with less hip and knee flexion (J.B. Taylor et al., 2016), higher forces (Cowley et al., 2006), and more exaggerated elements of dynamic valgus (A. Munro et al., 2012; J.B. Taylor et al., 2016) than soccer players. Additionally, basketball players may be weaker compared to soccer players, although previous investigations have been limited to testing of the quadriceps and hamstrings (Cheung et al., 2012). Considering that basketball and soccer players appear to show similar responses to training, prevention programs may need to emphasize these deficiencies when working with a basketball population. For example, basketball players may need to develop a more robust strength base prior to participating in high-level plyometric and agility training. Additionally, focus may need to be placed on technique, with feedback emphasizing soft landings and exaggerated hip and knee flexion. This was a primary component of the feedback given in our study, yet the training stimulus did not appear large enough to elicit meaningful changes, as neither basketball nor soccer players exhibited biomechanical adaptations after training. As such, future ACL injury prevention programs designed for basketball players may benefit from a modified design to account for the distinct biomechanical and neuromuscular profiles that may place basketball players at risk for ACL injury.

Interestingly, the sport-specific biomechanical adaptations that were observed in this study were identified during single-leg jump landing tasks. Observational analyses suggest that up to 70% of injuries occur during single-leg ground contact (Boden et al., 2009), yet screening procedures typically utilize double-leg tasks such as the DVJ to identify athletes at higher risk of injury. The single-leg tasks used in our study have good to excellent day-to-day reliability and performance consistency (J. B. Taylor et al., 2016), and may ultimately best differentiate high-risk biomechanics in basketball and soccer players (J.B. Taylor et al., 2016). In our study, basketball players exhibited relatively lower improvements in knee abduction measures during the SAG-SL task and greater improvements in knee flexion excursion during the FRONT-SL task than soccer players. In isolation, this evidence is conflicting because knee abduction is thought to be a risk factor for injury (Hewett et al., 2005), while greater levels of knee flexion may be protective (Sakane et al., 1999; Shimokochi & Shultz, 2008); however, these findings appear to be more a function of changes in the control groups than intervention groups (Figure 2). Regardless, similar to previous studies, single-leg tasks appear to best discriminate biomechanical movement patterns between basketball and soccer players (A. Munro et al., 2012; J.B. Taylor et al., 2016), suggesting that more emphasis on single-leg jump landings may be warranted in future screening and injury prevention studies.

This study indicates that basketball and soccer players respond similarly to the same training program. While this suggests that the lack of efficacy of ACL injury prevention programs in women's basketball may in part reflect the need for more sport-specific preventive training, this has yet to be investigated. It may be that basketball players, by virtue of their less protective biomechanical profiles and more rigorous multi-directional sports demands, may simply be more at risk for ACL injury, despite the chosen intervention. Thus, basketball-specific research is warranted. In fact, of all musculoskeletal injury prevention programs ever published in team-ball sports, 50% have been performed in soccer populations, compared to only 8% in basketball (O'Brien & Finch, 2014). Basketball may need to follow the leadership of soccer, as their major executive body, Fédération Internationale de Football Association (FIFA), has sponsored and promoted the FIFA 11+ Injury Prevention Programme to reduce general lower extremity and ACL injuries in the sport (Bizzini & Dvorak, 2015; Steffen et al., 2008). Yet, to date, no basketball-specific or basketball-sponsored injury prevention programs have been publicly advocated for by the Fédération Internationale de Basket-ball Association (FIBA) or other major administrative body. Promoting greater awareness of the prevalence of and ramifications from lower extremity and ACL injuries in the basketball population may help to improve attentional focus and effort during training. Considering high participation and injury rates in women's basketball (Ackerman, 2013; National Federation of State High School Associations, 2012), and the unanswered questions about the success of injury prevention programs, additional basketball-specific research is in dire need (Wojtys, 2015).

Limitations

Our biomechanical study was limited strictly to kinematics and kinetics, and did not measure changes in strength, muscle activation, or other neuromuscular characteristics that may result after training. Changes in strength or activation may influence injury risk, but may not be noticeable in kinematic or kinetic measures. Future studies that identify sport-specific hip and thigh strength, and timing and amplitude of lower extremity muscle activation may further elucidate the differential success rates of ACL injury prevention programs. Additionally, 6 weeks may not have been long enough to elicit meaningful changes in biomechanical strategies, yet middle- and high school athletes rarely have longer than 6 weeks of pre-season training to participate in these programs and successfully modify high-risk biomechanics prior to the start of competition. To date, we do not yet know the optimal dosage, timing, duration, and intensity that is necessary to prepare female athletes for competition within the constraints of current seasonal schedules. Further sport-specific analyses that can address these time-dependent adaptations and account for changes in both biomechanical and neuromuscular characteristics will best guide future injury prevention program design and implementation practices.

Conclusion

Women's basketball and soccer players largely exhibit similar biomechanical adaptations to a standard ACL injury prevention program after 6-weeks of training. Considering their similar responses, our results suggest that to optimize the success of ACL injury prevention programs in basketball players, future programs may need to account for their distinct sport-specific demands, mechanisms of injury and/or biomechanical profiles.

Tables and Figures

Figure 6.1. CONSORT Diagram Illustrating Participant Enrollment, Allocation, Follow-up, and Analysis Throughout the Study.

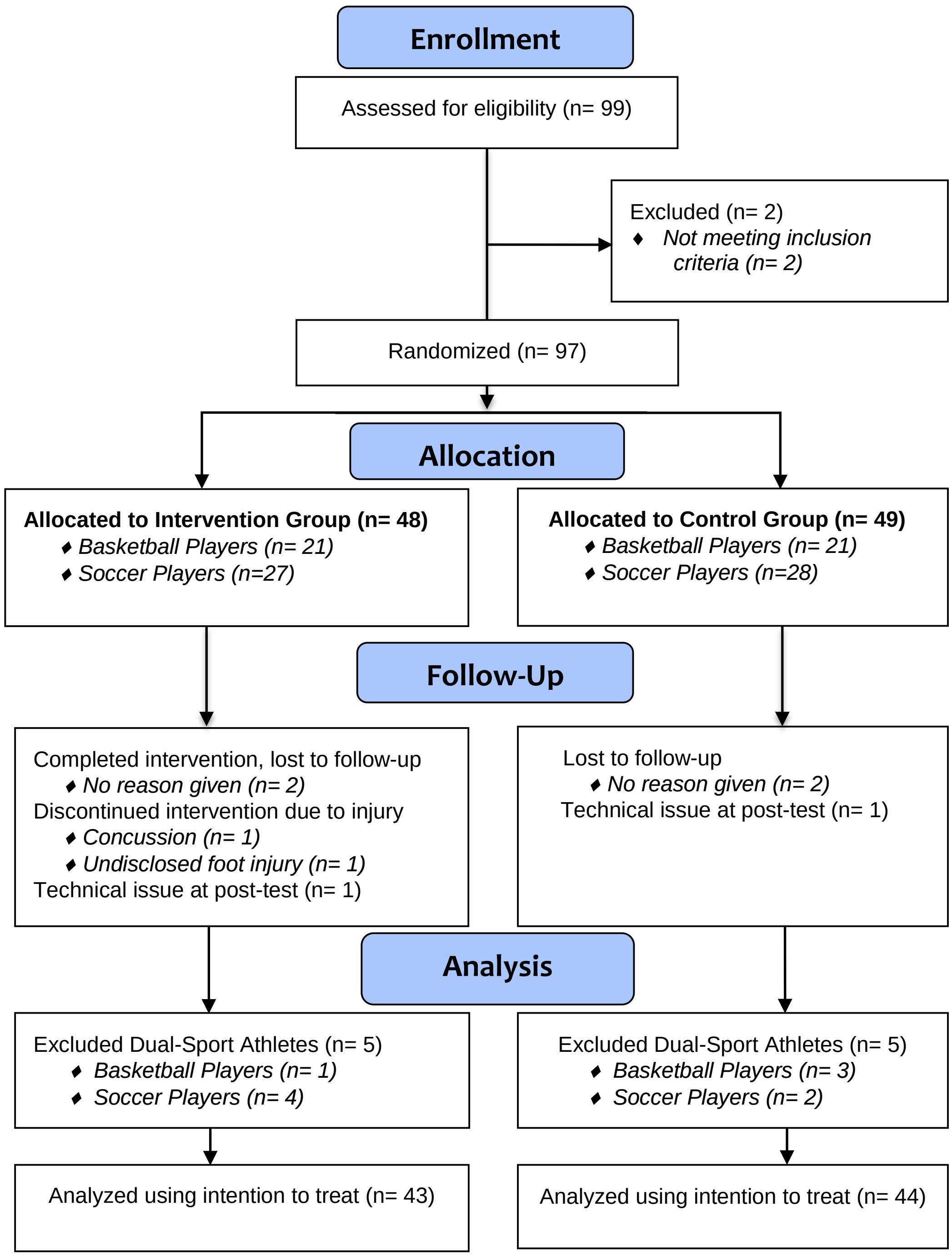


Figure 6.2. Ensemble Curves of a) Knee Abduction Angles During the SAG-SL Task, and (b) Knee Flexion Angles During the FRONT-SL Task for the Basketball (BB) and Soccer (SOC) Intervention Groups.

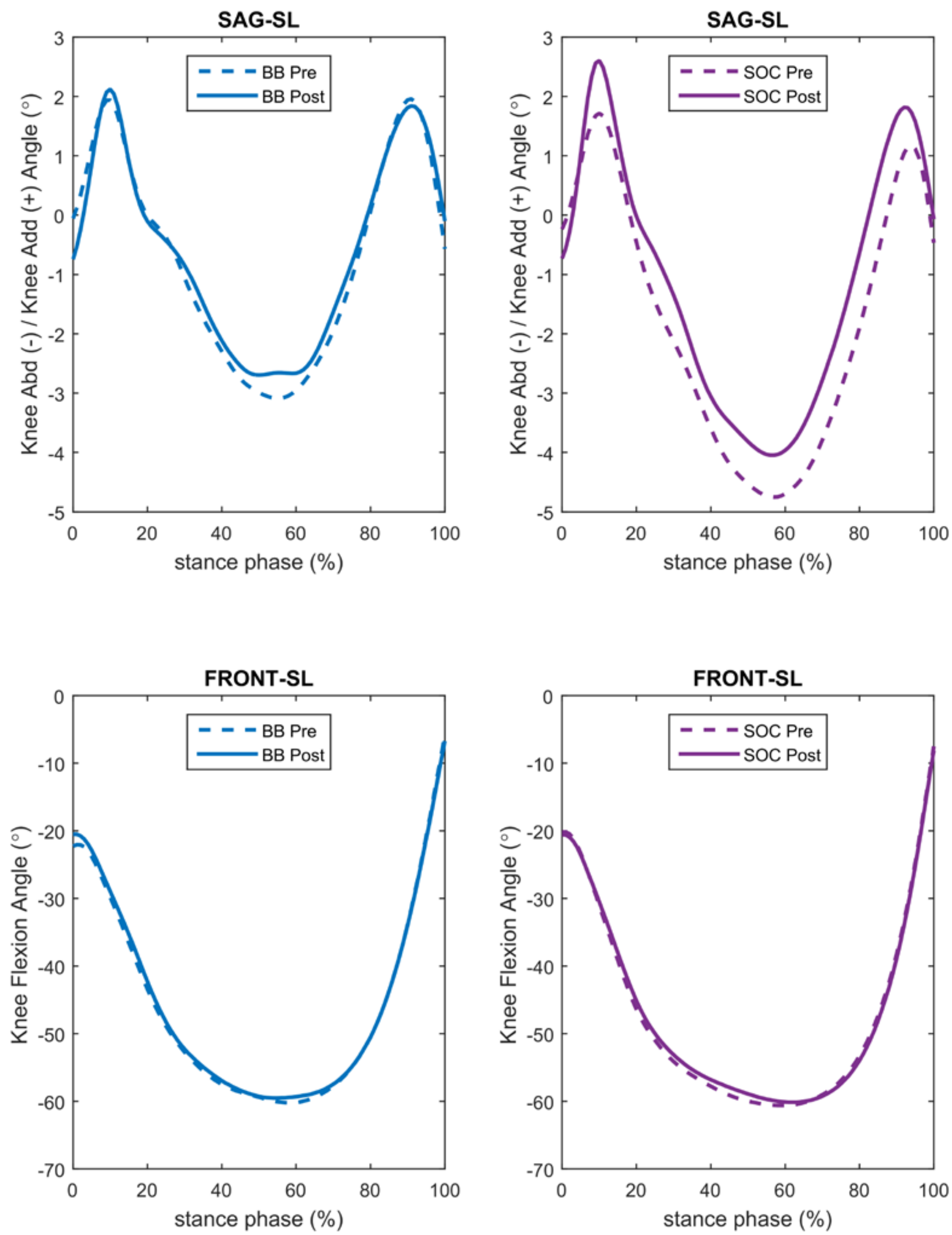


Table 6.1. Training Program Used in this Study (Originally Developed by LaBella et al, 2011)

WEEK 1	WEEK 2	WEEK 3-6
Jog	Jog	Jog
Dynamic Warm-Up*	Dynamic Warm-Up*	Dynamic Warm-Up*
	Strengthening	
Heel Raises[†]	Heel Raises[†]	Heel Raises[†]
Squats[†]	Squats[†]	Squats[†]
Plank/Side Plank[‡]	Plank/Side Plank[‡]	Plank/Side Plank[‡]
Push-ups[†]	Push-ups[†]	Push-ups[†]
Forward Lunge[†]	Lateral Lunge[†]	Lateral Lunge[†]
Supermans[†]	Diagonal Lunge[†]	Diagonal Lunge[†]
Swimmers[†]	Supermans[†]	Walking Lunge[†]
	Swimmers[†]	Supermans[†]
	Modified Supermans[†]	Swimmers[†]
		Modified Supermans[†]
	Plyometrics	
Ankle Bounces[‡]	Ankle Bounces[‡]	Ankle Bounces[‡]
Tuck Jumps[‡]	Tuck Jumps[‡]	Tuck Jumps[‡]
180 degree rotate[‡]	Squat Jumps[‡]	Squat Jumps[‡]
Squat Jump[‡]	Forward/Lateral Cone Jumps[‡]	Forward/Lateral Cone Jumps[‡]
DL Broad Jump for Distance[^]	Scissor Jumps[‡]	SL Hop, Hop, Stick[^]
Forward/Lateral Cone Jumps[‡]	Lateral Bounding[‡]	SL Jump for Distance[^]
SL Bound in Place[^]	SL Hop, Hop, Stick[^]	Jump to Bounding
	Broad Jump x3, Vertical Jump[^]	Diagonal Bounding
	Agility	
Shuttle Run[∞]	Shuttle Run[∞]	Shuttle Run[∞]
Diagonal Run[∞]	Diagonal Run[∞]	Diagonal Run[∞]
Lateral Shuffle[∫]	Lateral Shuffle[∫]	Lateral Shuffle[∫]

*dynamic warm-up included 2 lengths each of: jogging, skipping, carioca, side shuffle with arm swing, sprint at 75% maximum, high-knee skipping, high-knee carioca, sprint at 100% maximum, backward jog, bear crawl, butt kickers, backward jog half-length, turn and sprint, diagonal skipping, and arm swings, trunk rotations, and leg swings (10 each)

† activities performed for desired number of repetitions: week 1- 10 reps, week 2- 20 reps, week 3-6- 30 reps

‡ activities performed for desired amount of time: week 1- 10 seconds or reps, week 2- 20 seconds or reps, week 3-6- 30 seconds or reps

^ activities performed 5 times for double-leg (DL) and 5 times on each side for single-leg (SL) tasks

∞ agility exercises performed for 50 feet, 10 repetitions

∫ agility exercises performed for 15 feet, 10 repetitions

Table 6.2. Mean ± Standard Deviation Describing Intervention and Control Groups in Soccer and Basketball Populations.

	Basketball			**Soccer**		
	Intervention (n=20)	Control (n=18)	Total (n=38)	Intervention (n=23)	Control (n=26)	Total (n=49)
Age	15.4±1.1	15.8±1.4	15.6±1.3	15.4±0.8	15.6±1.6	15.5±1.3
Height (m)	1.68±0.08	1.72±0.06	1.70±0.07‡	1.62±0.05†	1.65±0.04†	1.64±0.05‡
Mass (kg)	66.9±12.5	63.0±7.9	65.0±10.6‡	54.6±7.0†	58.4±5.7†	56.6±6.5‡
BMI (m/kg^2)	23.6±3.2*	21.3±2.3*	22.5±3.0‡	20.8±2.2	21.4±2.1	21.1±2.1‡
Training volume (Days/week)	4.1±1.4	4.5±1.2	4.3±1.3	4.5±0.8	4.3±0.9	4.4±0.9

* significant difference between basketball intervention and control groups (p<.05)
† significant difference between soccer intervention and control groups (p<.05)
‡ significant difference between basketball and soccer players (p<.05)

Table 6.3. Mean ± Standard Deviations for Biomechanical Variables at the Pre- and Post- Test for Basketball and Soccer Players in the Intervention (Int) and Control (Cont) Groups During the DVJ task.

DVJ			Basketball		Soccer	
			Pre-	Post-	Pre-	Post-
Peak Angles (degrees)	Hip Flexion (+)	Int	57.3±9.6	56.9±9.3	58.8±8.6	58.8±10.0
		Cont	60.6±11.2	61.3±11.2	61.6±9.5	59.5±9.9
	Hip Adduction (+)	Int	0.9±4.6	-0.9±3.9	1.3±4.0	0.7±4.7
		Cont	3.6±6.2	3.6±5.8	1.4±5.5	1.1±5.4
	Hip Internal Rotation (+)	Int	-3.3±6.8	-3.1±8.8	-5.2±6.5	-1.7±4.3
		Cont	-2.9±6.1	-1.7±5.6	-4.4±5.0	-2.0±6.5
	Knee Flexion (-)	Int	-80.6±8.5	-80.9±8.4	-79.6±8.4	-79.7±8.7
		Cont	-80.6±8.0	-79.5±7.9	-83.7±7.9	-83.5±8.6
	Knee Abduction (-)	Int	-7.9±6.8	-8.8±8.5	-7.0±7.5	-5.0±4.8
		Cont	-9.2±5.9	-8.9±5.1	-8.2±5.0	-6.4±4.5
	Knee External Rotation (-)	Int	0.3±4.6	-1.2±6.1	-0.3±4.3	-0.6±5.1
		Cont	-1.0±6.0	-1.4±2.8	-2.3±5.0	-2.8±6.7
	Knee Internal Rotation (+)	Int	10.0±6.8	10.8±8.4	8.9±5.7	9.4±5.7
		Cont	8.9±5.7	8.6±4.4	8.7±5.2	9.0±5.7
Angular Excursions (degrees)	Hip Flexion	Int	30.4±10.0	27.8±11.1	31.6±11.2	33.0±12.6
		Cont	29.2±10.7	27.0±10.5	36.1±9.9	32.7±8.9
	Hip Adduction	Int	2.7±2.1	2.2±2.1	2.6±2.9	2.6±3.2
		Cont	6.2±4.2	6.8±4.2	3.4±4.5	3.2±4.1
	Hip Internal Rotation	Int	6.0±3.8	6.9±6.5	3.1±3.0	6.7±6.5
		Cont	5.7±4.8	4.1±4.1	3.7±4.2	7.2±5.2
	Knee Flexion	Int	62.0±10.7	62.5±11.5	61.7±10.8	62.3±10.4
		Cont	59.6±7.2	58.7±8.2	65.1±8.8	64.3±9.1
	Knee Abduction	Int	7.3±4.3	8.2±5.6	7.4±5.2	5.7±4.3
		Cont	8.4±4.6	8.5±3.7	7.6±4.1	5.9±3.8
	Knee External Rotation	Int	3.1±3.6	4.0±5.3	2.3±2.7	2.7±3.1
		Cont	3.5±4.0	2.5±3.4	2.3±3.5	3.8±4.2
	Knee Internal Rotation	Int	6.5±6.6	8.0±6.5	6.9±5.7	7.4±5.2
		Cont	6.4±5.8	7.5±5.5	8.7±4.2	7.9±4.5
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.00±0.27	0.98±0.33	1.08±0.22	1.24±0.3
		Cont	1.07±0.20	1.09±0.19	1.00±0.20	1.12±0.20
	Hip Adduction (+)	Int	0.21±0.14	0.19±0.18	0.18±0.14	0.20±0.19
		Cont	0.16±0.13	0.19±0.16	0.21±0.13	0.22±0.16
	Hip Internal Rotation (+)	Int	0.26±0.09	0.26±0.10	0.27±0.08	0.29±0.10
		Cont	0.26±0.08	0.29±0.12	0.27±0.08	0.27±0.08
	Knee Flexion (-)	Int	-1.06±0.15	-1.05±0.17	-1.06±0.24	-1.12±0.31
		Cont	-1.20±0.21	-1.25±0.27	-1.08±0.20	-1.12±0.22
	Knee Abduction (-)	Int	-0.26±0.13	-0.27±0.17	-0.20±0.12	-0.17±0.10
		Cont	-0.29±0.13	-0.31±0.14	-0.22±0.13	-0.16±0.10
	Knee External Rotation (-)	Int	-0.05±0.05	-0.05±0.05	-0.05±0.05	-0.05±0.05
		Cont	-0.03±0.04	-0.03±0.04	-0.05±0.04	-0.05±0.05
	Knee Internal Rotation (+)	Int	0.10±0.05	0.10±0.05	0.08±0.04	0.10±0.07
		Cont	0.13±0.06	0.14±0.08	0.08±0.04	0.07±0.05

Table 6.4. Mean ± Standard Deviations for Biomechanical Variables at the Pre- and Post- Test for Basketball and Soccer Players in the Intervention (Int) and Control (Cont) Groups During the SAG-DL task.

SAG-DL			Basketball		Soccer	
			Pre-	Post-	Pre-	Post-
Peak Angles (degrees)	Hip Flexion (+)	Int	61.5±6.1	60.4±7.1	61.4±7.5	61.3±9.0
		Cont	65.6±7.7	65.9±8.2	63.7±9.3	62.6±10.6
	Hip Adduction (+)	Int	0.2±3.1	0.2±4.7	0.6±4.7	0.7±4.9
		Cont	2.4±6.0	3.0±6.0	1.2±5.4	1.4±4.6
	Hip Internal Rotation (+)	Int	-1.2±8.8	0.2±9.9	-2.5±6.9	1.2±6.6
		Cont	0.8±7.8	1.4±7.8	-2.5±7.0	1.0±7.3
	Knee Flexion (-)	Int	-80.0±8.0	-80.0±7.8	-81.7±9.0	-81.4±7.5
		Cont	-81.4±8.0	-77.9±6.9	-84.4±8.4	-84.1±9.4
	Knee Abduction (-)	Int	-6.9±7.4	-8.8±8.0	-6.6±7.6	-3.8±4.6
		Cont	-9.6±4.8	-8.9±4.9	-7.9±4.8	5.9±4.5
	Knee External Rotation (-)	Int	1.5±6.4	-0.2±7.1	-1.3±4.4	-1.9±5.4
		Cont	-0.8±6.3	-1.0±4.3	-1.7±5.7	-2.2±5.8
	Knee Internal Rotation (+)	Int	12.1±6.6	12.2±8.6	10.4±5.7	11.4±6.3
		Cont	10.3±5.2	9.4±4.8	9.8±4.2	10.8±5.4
Angular Excursions (degrees)	Hip Flexion	Int	13.0±6.9	13.7±7.2	19.2±8.7	21.1±9.5
		Cont	14.4±9.1	10.6±6.9	19.7±11.1	19.7±11.2
	Hip Adduction	Int	2.7±2.0	3.1±3.6	3.6±3.7	2.9±3.4
		Cont	7.3±4.2	6.6±4.1	4.3±4.4	3.6±4.0
	Hip Internal Rotation	Int	9.8±6.4	12.1±7.4	4.1±3.4	10.2±9.8
		Cont	7.2±6.0	6.3±5.7	7.9±6.7	12.5±7.8
	Knee Flexion	Int	55.1±10.4	58.9±8.6	62.8±9.8	65.3±7.7
		Cont	58.2±8.2	51.7±11.0	63.4±10.5	63.4±8.7
	Knee Abduction	Int	5.9±4.2	7.1±5.0	7.3±5.4	4.4±3.8
		Cont	8.6±5.0	8.0±3.3	7.3±3.9	4.7±3.7
	Knee External Rotation	Int	4.2±4.7	6.3±6.3	1.9±2.9	4.0±6.1
		Cont	3.0±4.2	2.6±2.7	3.2±4.7	6.3±5.6
	Knee Internal Rotation	Int	6.5±5.8	6.1±5.7	9.8±5.7	9.3±6.1
		Cont	8.2±5.5	7.8±3.3	8.3±5.5	6.7±4.5
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.21±0.32	1.23±0.33	1.21±0.26	1.32±0.27
		Cont	1.22±0.25	1.24±0.22	1.23±0.32	1.38±0.33
	Hip Adduction (+)	Int	0.15±0.13	0.21±0.17	0.15±0.13	0.15±0.14
		Cont	0.15±0.19	0.18±0.16	0.20±0.16	0.23±0.21
	Hip Internal Rotation (+)	Int	0.33±0.11	0.34±0.09	0.31±0.10	0.28±0.09
		Cont	0.30±0.10	0.34±0.13	0.33±0.09	0.32±0.09
	Knee Flexion (-)	Int	-1.19±0.16	-1.20±0.23	-1.26±0.25	-1.23±0.32
		Cont	-1.31±0.26	-1.38±0.25	-1.26±0.24	-1.27±0.26
	Knee Abduction (-)	Int	-0.23±0.13	-0.24±0.18	-0.22±0.13	-0.15±0.09
		Cont	-0.29±0.11	-0.28±0.14	-0.23±0.11	-0.17±0.12
	Knee External Rotation (-)	Int	-0.05±0.06	-0.06±0.07	-0.03±0.04	-0.04±0.04
		Cont	-0.01±0.06	-0.02±0.07	-0.05±0.06	-0.05±0.06
	Knee Internal Rotation (+)	Int	0.12±0.07	0.11±0.06	0.12±0.05	0.12±0.05
		Cont	0.17±0.07	0.16±0.09	0.10±0.06	0.09±0.06

Table 6.5. Mean ± Standard Deviations for Biomechanical Variables at the Pre- and Post- Test for Basketball and Soccer Players in the Intervention (Int) and Control (Cont) Groups During the SAG-SL Task.

SAG-SL			Basketball		Soccer	
			Pre-	Post-	Pre-	Post-
Peak Angles (degrees)	Hip Flexion (+)	Int	46.7±7.7	46.3±6.1	43.4±7.5	44.3±8.2
		Cont	48.8±6.7	49.2±6.5	46.4±8.2	44.6±8.8
	Hip Adduction (+)	Int	8.7±5.1	9.9±4.8	9.6±5.0	11.4±4.7
		Cont	10.0±4.6	8.5±4.4	9.8±4.3	9.5±5.1
	Hip Internal Rotation (+)	Int	-1.0±6.5	2.5±7.2	-2.5±9.1	-0.3±6.2
		Cont	-2.6±5.9	-1.0±6.7	-2.5±7.4	-0.3±8.6
	Knee Flexion (-)	Int	-55.7±6.6	-54.8±6.5	-55.9±6.5	-55.5±6.0
		Cont	-56.0±6.7	-53.7±5.7	-58.6±7.4	-57.6±5.8
	Knee Abduction (-)	Int	-4.5±6.1	-5.4±6.9*†	-3.8±5.7	-2.3±4.0†
		Cont	-6.2±5.1	-3.6±4.3*	-4.9±3.8	-4.4±4.0
	Knee External Rotation (-)	Int	-0.2±6.5	-0.3±6.9	-0.7±4.7	-1.9±5.5
		Cont	-0.8±5.0	-1.4±4.3	-1.7±4.9	-2.2±7.1
	Knee Internal Rotation (+)	Int	9.7±4.9	11.1±7.7	9.8±4.7	11.2±6.2
		Cont	9.6±4.5	8.0±3.4	10.3±5.0	11.0±5.5
Angular Excursions (degrees)	Hip Flexion	Int	9.3±5.2	7.9±4.9	10.9±6.3	10.8±6.5
		Cont	8.1±4.9	6.0±3.7	10.1±6.7	8.5±5.6
	Hip Adduction	Int	9.4±3.5	9.3±2.4	9.7±4.4	9.6±4.0
		Cont	10.1±4.5	8.1±3.3	11.6±4.5	10.2±4.2
	Hip Internal Rotation	Int	8.0±4.1	10.5±5.9	6.3±4.0	10.3±6.6
		Cont	7.6±4.7	5.6±2.9	7.3±3.6	10.4±5.0
	Knee Flexion	Int	38.1±7.4	37.9±6.6	42.0±5.7	42.4±6.7
		Cont	37.2±5.9	33.5±5.8	42.4±7.7	41.0±6.2
	Knee Abduction	Int	4.2±3.6	4.3±3.7*†	3.9±3.7	2.3±2.4†
		Cont	5.0±3.9	3.1±2.8*	4.1±2.6	3.3±2.8
	Knee External Rotation	Int	3.7±3.2	5.5±4.5	2.3±2.0	6.1±5.0
		Cont	4.1±3.8	2.2±2.5	3.8±3.7	6.5±5.0
	Knee Internal Rotation	Int	6.3±5.6	5.9±5.3	8.1±3.5	7.0±4.4
		Cont	6.3±4.2	7.1±3.3	8.2±4.3	6.7±4.3
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.68±0.40	1.87±0.40	1.67±0.34	1.89±0.34
		Cont	1.79±0.40	1.87±0.23	1.66±0.37	1.77±0.36
	Hip Adduction (+)	Int	1.01±0.24	0.98±0.25	0.98±0.24	1.05±0.25
		Cont	0.94±0.20	0.43±0.18	1.08±0.19	1.09±0.20
	Hip Internal Rotation (+)	Int	0.42±0.10	0.42±0.12	0.36±0.11	0.39±0.11
		Cont	0.43±0.13	0.44±0.18	0.40±0.12	0.42±0.13
	Knee Flexion (-)	Int	-1.58±0.24	-1.51±0.31	-1.58±0.31	-1.54±0.34
		Cont	-1.62±0.28	-1.64±0.39	-1.70±0.28	-1.66±0.27
	Knee Abduction (-)	Int	-0.16±0.15	-0.21±0.20	-0.09±0.14	-0.06±0.15
		Cont	-0.16±0.17	-0.14±0.13	-0.08±0.10	-0.07±0.10
	Knee External Rotation (-)	Int	-0.38±0.13	-0.32±0.11	-0.37±0.09	-0.38±0.11
		Cont	-0.34±0.07	-0.32±0.10	-0.41±0.06	-0.42±0.08
	Knee Internal Rotation (+)	Int	-0.01±0.03	0.01±0.04	-0.003±0.02	0.005±0.04
		Cont	0.01±0.04	0.002±0.03	-0.01±0.02	-0.01±0.02

* significant difference between basketball control and intervention groups after controlling for pre-test values (p<.05)

† significant difference between basketball and soccer intervention groups after controlling for pre-test values(p<.05)

Table 6.6. Mean ± Standard Deviations for Biomechanical Variables at the Pre- and Post- Test for Basketball and Soccer Players in the Intervention (Int) and Control (Cont) Groups During the FRONT-DL Task.

FRONT-DL			Basketball Pre-	Basketball Post-	Soccer Pre-	Soccer Post-
Peak Angles (degrees)	Hip Flexion (+)	Int	56.2±6.5	53.3±8.3	55.1±8.3	55.1±10.6
		Cont	54.6±10.4	56.6±11.3	59.5±9.7	56.5±11.0
	Hip Adduction (+)	Int	-4.3±4.6	-6.1±4.1	-4.9±5.7	-4.4±5.5
		Cont	-0.8±8.3	-1.8±6.4	-4.5±5.3	-4.9±5.3
	Hip Internal Rotation (+)	Int	2.5±9.9	4.8±11.4	2.3±7.8	5.2±6.8
		Cont	3.6±7.7	7.1±5.6	2.2±5.9	7.2±7.5
	Knee Flexion (-)	Int	-73.1±6.2	-70.7±7.5	-72.3±7.0	-70.9±7.8
		Cont	-70.1±8.5	-69.3±6.7	-75.6±7.1	-74.7±8.3
	Knee Abduction (-)	Int	-8.6±7.3	-8.5±7.1	-7.5±6.0	-4.1±4.4
		Cont	-8.6±5.4	-8.3±5.2	-6.7±5.0	-5.8±4.3
	Knee External Rotation (-)	Int	-0.9±6.0	-2.4±7.7	-3.3±4.7	-5.1±4.4
		Cont	-1.7±6.7	-0.8±3.2	-5.4±6.4	-4.7±5.4
	Knee Internal Rotation (+)	Int	10.5±6.3	12.0±8.1	8.2±6.1	8.8±5.2
		Cont	9.5±6.7	9.5±5.3	7.2±6.4	8.1±4.8
Angular Excursions (degrees)	Hip Flexion	Int	19.7±10.7	17.9±10.2	25.4±11.4	28.0±11.5
		Cont	15.3±9.8	12.5±10.0	29.1±11.3	23.2±9.7
	Hip Adduction	Int	7.7±4.8	6.0±4.1	8.8±5.3	8.1±5.1
		Cont	10.6±4.4	10.4±4.3	7.9±6.0	7.1±5.4
	Hip Internal Rotation	Int	8.4±6.5	10.4±7.0	7.1±4.2	9.3±8.1
		Cont	7.1±4.8	7.7±4.7	6.3±4.4	10.3±6.9
	Knee Flexion	Int	43.5±12.8	43.7±10.5	49.6±10.8	49.0±10.3
		Cont	38.0±11.7	34.6±11.7	50.8±11.1	47.2±9.6
	Knee Abduction	Int	5.1±4.2	5.1±3.8	4.6±3.8	2.9±2.9
		Cont	5.1±4.7	3.7±3.5	4.2±3.2	2.9±3.0
	Knee External Rotation	Int	2.1±2.5	1.8±2.8	1.7±2.1	2.2±4.3
		Cont	1.3±1.4	0.9±1.2	1.7±3.0	2.4±3.7
	Knee Internal Rotation	Int	9.2±5.4	13.3±5.8	9.8±4.8	11.7±5.1
		Cont	9.9±4.6	9.4±5.0	10.9±4.0	10.6±5.3
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.12±0.32	1.11±0.31	1.18±0.24	1.35±0.27
		Cont	1.18±0.32	1.13±0.29	1.16±0.33	1.35±0.28
	Hip Adduction (+)	Int	0.04±0.12	0.05±0.16	0.12±0. 19	0.11±0.16
		Cont	0.08±0.26	0.06±0.23	0.07±0.13	0.14±0.19
	Hip Internal Rotation (+)	Int	0.31±0.10	0.33±0.13	0.41±0.14	0.36±0.10
		Cont	0.33±0.12	0.35±0.13	0.35±0.10	0.38±0.09
	Knee Flexion (-)	Int	-1.23±0.28	-1.26±0.26	-1.34±0.50	-1.18±0.38
		Cont	-1.41±0.27	-1.40±0.33	-1.17±0.30	-1.24±0.31
	Knee Abduction (-)	Int	-0.29±0.15	-0.33±0.18	-0.34±0.27	-0.20±0.09
		Cont	-0.35±0.16	-0.38±0.20	-0.24±0.12	-0.21±0.11
	Knee External Rotation (-)	Int	-0.04±0.07	-0.03±0.06	-0.06±0.07	-0.07±0.06
		Cont	-0.01±0.08	0.01±0.07	-0.05±0.07	-0.07±0.07
	Knee Internal Rotation (+)	Int	0.15±0.08	0.15±0.08	0.16±0.08	0.12±0.04
		Cont	0.18±0.09	0.20±0.11	0.14±0.07	0.14±0.07

Table 6.7. Mean ± Standard Deviations for Biomechanical Variables at the Pre- and Post- Test for Basketball and Soccer Players in the Intervention (Int) and Control (Cont) Groups During the FRONT-SL Task.

FRONT-SL			Basketball		Soccer	
			Pre-	Post-	Pre-	Post-
Peak Angles (degrees)	Hip Flexion (+)	Int	46.7±6.9	46.8±6.9	47.9±6.3	47.1±7.2
		Cont	47.4±7.1	50.6±7.4	47.4±8.6	46.2±9.2
	Hip Adduction (+)	Int	-0.3±5.3	-1.1±5.8	5.8±6.2	4.5±5.2
		Cont	2.1±6.3	1.3±7.1	5.4±6.4	6.0±6.8
	Hip Internal Rotation (+)	Int	6.4±8.1	8.4±10.4	5.2±8.9	8.0±8.2
		Cont	2.7±8.1	4.1±7.5	2.8±7.6	6.0±7.8
	Knee Flexion (-)	Int	-58.2±5.7	-57.8±6.5	-59.5±5.9	-58.0±6.4
		Cont	-58.3±5.9	-58.4±4.4	-61.4±5.5	-61.1±6.0
	Knee Abduction (-)	Int	-6.0±6.2	-5.6±7.6	-5.3±5.6	-2.4±3.4
		Cont	-6.5±4.4	-5.8±4.2	-5.7±4.7	-4.7±4.6
	Knee External Rotation (-)	Int	-1.4±6.2	-4.5±8.9	-2.2±5.1	-5.2±5.8
		Cont	-2.3±6.8	-0.3±5.1	-2.5±5.1	-3.8±6.5
	Knee Internal Rotation (+)	Int	10.6±5.3	10.4±7.5	10.0±5.5	9.9±5.2
		Cont	8.3±5.3	8.7±4.9	9.2±5.2	9.3±6.1
Angular Excursions (degrees)	Hip Flexion	Int	12.5±7.9	12.2±6.4	18.5±8.6	18.0±8.2
		Cont	11.6±7.4	9.9±7.2	16.0±8.1	14.8±7.3
	Hip Adduction	Int	19.6±4.7	18.9±4.6	22.8±5.8	22.6±5.6
		Cont	22.4±5.6	20.4±4.9	22.8±5.6	23.0±5.6
	Hip Internal Rotation	Int	9.4±5.1	12.0±6.4	4.8±4.5	7.0±4.0
		Cont	5.1±3.4	5.3±3.7	5.0±4.1	8.7±6.2
	Knee Flexion	Int	35.2±8.7	36.7±8.1*	39.9±7.3	37.8±6.8
		Cont	31.9±8.3	30.1±7.4	38.7±7.6	38.3±6.1
	Knee Abduction	Int	4.3±3.2	4.4±4.1	4.4±3.1	2.6±2.7
		Cont	5.7±3.3	4.8±2.9	5.4±2.7	4.2±3.3
	Knee External Rotation	Int	6.5±4.0	8.8±5.2	3.9±3.8	4.5±3.1
		Cont	4.8±4.0	3.8±3.0	3.1±2.8	5.2±4.6
	Knee Internal Rotation	Int	5.4±5.9	6.0±6.2	8.4±4.4	10.6±4.8
		Cont	5.7±3.9	5.2±3.0	8.6±4.3	8.0±4.8
Peak External Moments (Nm/kg*m)	Hip Flexion (+)	Int	1.27±0.36	1.30±0.40	1.39±0.21	1.49±0.30
		Cont	1.26±0.34	1.34±0.24	1.39±0.32	1.48±0.29
	Hip Adduction (+)	Int	0.58±0.20	0.54±0.21	0.73±0.20	0.72±0.18
		Cont	0.60±0.28	0.55±0.30	0.78±0.17	0.85±0.20
	Hip Internal Rotation (+)	Int	0.44±0.15	0.43±0.12	0.42±0.11	0.41±0.12
		Cont	0.38±0.16	0.4.1±0.12	0.40±0.13	0.40±0.13
	Knee Flexion (-)	Int	-1.29±0.21	-1.24±0.31	-1.29±0.25	-1.18±0.27
		Cont	-1.27±0.28	-1.31±0.30	-1.39±0.22	-1.34±0.21
	Knee Abduction (-)	Int	-0.28±0.12	-0.31±0.13	-0.22±0.12	-0.20±0.12
		Cont	-0.27±0.10	-0.26±0.09	-0.18±0.07	-0.17±0.07
	Knee External Rotation (-)	Int	-0.22±0.07	-0.20±0.10	-0.30±0.07	-0.31±0.10
		Cont	-0.24±0.10	-0.21±0.08	-0.32±0.08	-0.34±0.08
	Knee Internal Rotation (+)	Int	0.08±0.05	0.08±0.04	0.06±0.06	0.06±0.06
		Cont	0.08±0.06	0.08±0.04	0.05±0.03	0.04±0.03

* significant difference between basketball control and intervention groups after controlling for pre-test values (p<.05)

CHAPTER VII

EXECUTIVE SUMMARY

Past evidence suggests that ACL injury prevention programs do not successfully reduce the risk of injury in women's basketball players, especially when compared to women's soccer players. Considering the high participation and ACL injury rates in women's basketball, understanding the lack of success in these programs is critical before future programs can be designed. This is the first study to attempt to comprehensively investigate underlying causes for these sport-specific differences in success rates of ACL injury prevention programs. Theoretically, this discrepancy could be attributed to differences in sport-specific responses to training (i.e. for some reason basketball players do not respond in the same way to the same stimulus), or that current programs do not sufficiently address the unique single-leg and frontal plane demands of basketball that are more represented in their reported injury mechanisms. We hypothesized that basketball and soccer players would respond similarly to the same training stimulus, but that basketball players would demonstrate significantly different biomechanical strategies during jump landings. Further, we expected that any biomechanical changes identified would be more prevalent during double-leg sagittal than other frontal plane or single-leg jump landing tasks, since current programs primarily emphasize sagittal plane activities during training. If our hypotheses were correct, it would suggest that the neuromuscular training prescribed during ACL injury prevention programs does not provide an effective training stimulus to address the distinct, high-risk biomechanical profiles of female basketball players.

The results partially confirmed the research hypotheses. Basketball players did employ higher risk landing strategies, including stiff-legged landings with lesser levels of hip and knee flexion excursion, during basketball-specific jump landings in the frontal plane and on a single-leg, and basketball and soccer players generally exhibited similar responses to the training program. Additionally, minimal biomechanical changes were identified across sports, suggesting a similar response to training, however, biomechanical adaptations were largely the same across tasks. Thus, regardless of the nature of the jump landing task, current warm-up based injury prevention programs (such as the one used in this study) may not provide the adequate volume or intensity needed to stimulate biomechanical changes after 6-weeks of training, leaving basketball players at a continued high-risk for injury because of the higher-risk biomechanics that they employ.

This study is expected to impact exercise prescription in future basketball-specific ACL injury prevention programs. Sports medicine professionals will need to account for the length of dedicated training time (i.e. length of pre- or off-season) and prescribe a training regimen with a large enough volume and intensity to elicit neuromuscular and/or biomechanical changes prior to competition. Additionally, future programs may need to emphasize softer landing techniques across a variety of jump landing tasks to more effectively reduce the high-risk landing strategies, and result in greater knee protection during basketball activities. Specifically, a greater emphasis needs to be placed on encouraging larger levels of hip and knee flexion during jumping and landing. This may occur through more optimized modes of technique feedback using externally-focused verbal cues, real-time visual feedback, or more advanced biofeedback technology. Considering that high-risk biomechanics are more prevalent during more complex landing tasks and that basketball requires frequent single-leg landings and frontal plane movements, future basketball-specific programs should also emphasize a more specific progression of exercises that transition from double- to single-leg and sagittal to non-sagittal plane activities.

However, the results of this study also highlight questions that remain unanswered and may provide important directions for future research. Our results indicate that the 6-week ACL injury prevention program did not produce meaningful changes in the lower extremity kinematics or kinetics thought to put an athlete at risk for injury. Many female athletes do not have the luxury of extended off- or pre-season periods in which they can prioritize preventive training. Participants in our study exhibited a variety of positive, negative and neutral responses to the program, and deeper analysis of the dataset may help elucidate factors that characterize responders versus non-responders to this type of training. Thus, future research, whether through addressing the characteristics of non-responders, changing the exercise prescription to better match with sport demands, or optimizing feedback techniques for the higher risk biomechanics in basketball, should focus on how to elicit meaningful biomechanical adaptations over a shorter duration.

To date, research has demonstrated that this and other low-intensity, warm-up based prevention programs have been successful at reducing ACL injury rates. However, we failed to demonstrate appreciable biomechanical alterations in response to one of these programs. As such, the mechanism by which these programs reduce injury rates remains unknown. More extensive analysis into other potential biomechanical and neuromuscular adaptations (i.e. muscle activation, strength) that were not measured in this study are necessary. Similar, long-term biomechanical studies using wearable technology may also elucidate athlete responses to these programs in a more realistic environment and provide further insight into such variables as the shoe-surface interface, sport activity demands, and unanticipated, reactive movements that a laboratory study cannot perfectly simulate.

Finally, more qualitative research may be warranted in women's basketball players. Throughout the recruitment, testing and training process, there were noticeable differences between sports in the awareness of ACL injuries, the perceived importance of preventive training, and the effort and attentional levels of coaches, parents and athletes. Basketball has been largely forgotten in ACL injury prevention research, often lumped together with soccer, handball, and/or volleyball. Thus, despite the high incidence rates, ACL injuries have been far less publicized in women's basketball. In order to improve public awareness and commitment to injury prevention in basketball, a top-down approach, with the major national and international basketball administrative bodies following the lead of soccer organizations may be needed to prioritize the long-term health of the basketball athlete. Ultimately, to truly optimize injury prevention in basketball players, significant further research is needed.

REFERENCES

Ackerman, V. (2013). *Division 1 women's basketball white paper prepared for the ncaa*. (National Collegiate Athletic Association) Retrieved from NCAA website: http://www.ncaa.org/sites/default/files/NCAAWBBWHITEPAPER_0.pdf.

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. *The American Journal of Sports Medicine, 33*(4), 524-530.

Arendt, E., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. Ncaa data and review of literature. *The American Journal of Sports Medicine, 23*(6), 694-701.

Arms, S. W., Pope, M. H., Johnson, R. J., Fischer, R. A., Arvidsson, I., & Eriksson, E. (1984). The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. *The American Journal of Sports Medicine, 12*(1), 8-18.

Baechle, T. R., & Earle, R. W. (2000). *Essentials of strength and conditioning* (2nd ed.). Champaign, IL: Human Kinetics.

Bangsbo, J., Norregaard, L., & Thorso, F. (1991). Activity profile of competition soccer. *Canadian Journal of Sport Sciences 16*(2), 110-116.

Barber Foss, K. D., Myer, G. D., & Hewett, T. E. (2014). Epidemiology of basketball, soccer, and volleyball injuries in middle-school female athletes. *The Physician and Sportsmedicine, 42*(2), 146-153.

Bates, N. A., Ford, K. R., Myer, G. D., & Hewett, T. E. (2013a). Impact differences in ground reaction force and center of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. *Journal of Biomechanics, 46*(7), 1237-1241.

Bates, N. A., Ford, K. R., Myer, G. D., & Hewett, T. E. (2013b). Kinetic and kinematic differences between first and second landings of a drop vertical jump task: Implications for injury risk assessments. *Clinical Biomechanics, 28*(4), 459-466.

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *Journal of Biomechanics, 23*(6), 617-621.

Ben Abdelkrim, N., El Fazaa, S., & El Ati, J. (2007). Time-motion analysis and physiological data of elite under-19-year-old basketball players during competition. *British Journal of Sports Medicine, 41*(2), 69-75; discussion 75.

Benjaminse, A., Gokeler, A., Dowling, A. V., Faigenbaum, A., Ford, K. R., Hewett, T. E., . . . Myer, G. D. (2015). Optimization of the anterior cruciate ligament injury prevention paradigm: Novel feedback techniques to enhance motor learning and reduce injury risk. *The Journal of Orthopaedic and Sports Physical Therapy*, 1-46.

Benjaminse, A., Welling, W., Otten, B., & Gokeler, A. (2014). Novel methods of instruction in acl injury prevention programs, a systematic review. *Physical Therapy in Sport*.

Bentley, J. A., Ramanathan, A. K., Arnold, G. P., Wang, W., & Abboud, R. J. (2011). Harmful cleats of football boots: A biomechanical evaluation. *Foot and Ankle Surgery, 17*(3), 140-144.

Bizzini, M., & Dvorak, J. (2015). Fifa 11+: An effective programme to prevent football injuries in various player groups worldwide-a narrative review. *British Journal of Sports Medicine, 49*(9), 577-579.

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical demands of different positions in fa premier league soccer. *Journal of Sports Science & Medicine, 6*, 63-70.

Boden, B. P., Dean, G. S., Feagin, J. A., Jr., & Garrett, W. E., Jr. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578.

Boden, B. P., Torg, J. S., Knowles, S. B., & Hewett, T. E. (2009). Video analysis of anterior cruciate ligament injury: Abnormalities in hip and ankle kinematics. *The American Journal of Sports Medicine, 37*(2), 252-259.

Brito, J., Rebelo, A., Soares, J. M., Seabra, A., Krustrup, P., & Malina, R. M. (2011). Injuries in youth soccer during the preseason. *Clinical Journal of Sport Medicine, 21*(3), 259-260.

Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2014). Comparative adaptations of lower limb biomechanics during uni-lateral and bi-lateral landings after different neuromuscular-based acl injury prevention protocols. *Journal of strength and conditioning research*.

Butler, D. L., Noyes, F. R., & Grood, E. S. (1980). Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *The Journal of Bone and Joint Surgery. American Volume, 62*(2), 259-270.

Butler, R. J., Hillstrom, H., Song, J., Richards, C. J., & Davis, I. S. (2008). Arch height index measurement system: Establishment of reliability and normative values. *Journal of the American Podiatric Medical Association*, *98*(2), 102-106.

Cerulli, G., Benoit, D. L., Lamontagne, M., Caraffa, A., & Liti, A. (2003). In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: Case report. *Knee Surgery, Sports Traumatology, Arthroscopy 11*(5), 307-311.

Chappell, J. D., & Limpisvasti, O. (2008). Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *The American Journal of Sports Medicine, 36*(6), 1081-1086.

Cheung, R. T., Smith, A. W., & Wong del, P. (2012). H:Q ratios and bilateral leg strength in college field and court sports players. *Journal of Human Kinetics, 33*, 63-71.

Chimera, N. J., Swanik, K. A., Swanik, C. B., & Straub, S. J. (2004). Effects of plyometric training on muscle-activation strategies and performance in female athletes. *Journal of Athletic Training, 39*(1), 24-31.

Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H., & McGivern, J. (2007). Characteristics of anterior cruciate ligament injuries in australian football. *Journal of Science and Medicine in Sport, 10*(2), 96-104.

Cowley, H. R., Ford, K. R., Myer, G. D., Kernozek, T. W., & Hewett, T. E. (2006). Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. *Journal of Athletic Training, 41*(1), 67-73.

Csintalan, R. P., Inacio, M. C., & Funahashi, T. T. (2008). Incidence rate of anterior cruciate ligament reconstructions. *The Permanente Journal, 12*(3), 17-21.

Dawson, S. J., & Herrington, L. (2015). Improving single-legged-squat performance: Comparing 2 training methods with potential implications for injury prevention. *Journal of Athletic Training, 50*(9), 921-929.

Deitch, J. R., Starkey, C., Walters, S. L., & Moseley, J. B. (2006). Injury risk in professional basketball players: A comparison of women's national basketball association and national basketball association athletes. *The American Journal of Sports Medicine, 34*(7), 1077-1083.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *The American Journal of Sports Medicine, 37*(11), 2194-2200.

Draganich, L. F., & Vahey, J. W. (1990). An in vitro study of anterior cruciate ligament strain induced by quadriceps and hamstrings forces. *Journal of Orthopaedic Research, 8*(1), 57-63.

Drakos, M. C., Hillstrom, H., Voos, J. E., Miller, A. N., Kraszewski, A. P., Wickiewicz, T. L., . . . O'Brien, S. J. (2010). The effect of the shoe-surface interface in the development of anterior cruciate ligament strain. *Journal of Biomechanical Engineering, 132*(1), 011003.

Durselen, L., Claes, L., & Kiefer, H. (1995). The influence of muscle forces and external loads on cruciate ligament strain. *The American Journal of Sports Medicine, 23*(1), 129-136.

Faude, O., Junge, A., Kindermann, W., & Dvorak, J. (2005). Injuries in female soccer players: A prospective study in the german national league. *The American Journal of Sports Medicine, 33*(11), 1694-1700.

Ford, K. R., DiCesare, C. A., Myer, G. D., & Hewett, T. E. (2014). Real-time biofeedback to target risk of anterior cruciate ligament injury: A technical report for injury prevention and rehabilitation. *Journal of Sport Rehabilitation, Technical Notes*(13).

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise, 35*(10), 1745-1750.

Ford, K. R., Myer, G. D., Smith, R. L., Byrnes, R. N., Dopirak, S. E., & Hewett, T. E. (2005). Use of an overhead goal alters vertical jump performance and biomechanics. *Journal of Strength and Conditioning Research, 19*(2), 394-399.

Ford, K. R., Myer, G. D., Smith, R. L., Vianello, R. M., Seiwert, S. L., & Hewett, T. E. (2006). A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clinical Biomechanics, 21*(1), 33-40.

Ford, K. R., Nguyen, A. D., Dischiavi, S. L., Hegedus, E. J., Zuk, E. F., & Taylor, J. B. (2015). An evidence-based review of hip-focused neuromuscular exercise interventions to address dynamic lower extremity valgus. *Open Access Journal of Sports Medicine, 6*, 291-303.

Gagnier, J. J., Morgenstern, H., & Chess, L. (2013). Interventions designed to prevent anterior cruciate ligament injuries in adolescents and adults: A systematic review and meta-analysis. *The American Journal of Sports Medicine, 41*(8), 1952-1962.

Gerritsen, K. G., Nachbauer, W., & van den Bogert, A. J. (1996). Computer simulation of landing movement in downhill skiing: Anterior cruciate ligament injuries. *Journal of Biomechanics, 29*(7), 845-854.

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of science and medicine in sport / Sports Medicine Australia, 12*(6), 622-627.

Gilchrist, J., Mandelbaum, B. R., Melancon, H., Ryan, G. W., Silvers, H. J., Griffin, L. Y., . . . Dvorak, J. (2008). A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *The American Journal of Sports Medicine, 36*(8), 1476-1483.

Goetschius, J., Smith, H. C., Vacek, P. M., Holterman, L. A., Shultz, S. J., Tourville, T. W., . . . Beynnon, B. D. (2012). Application of a clinic-based algorithm as a tool to identify female athletes at risk for anterior cruciate ligament injury: A prospective cohort study with a nested, matched case-control analysis. *The American Journal of Sports Medicine, 40*(9), 1978-1984.

Gokeler, A., Benjaminse, A., Hewett, T. E., Paterno, M. V., Ford, K. R., Otten, E., & Myer, G. D. (2013). Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: Implications for motor control and reduction of second injury risk. *Sports Medicine*, *43*(11), 1065-1074.

Gomez, E., DeLee, J. C., & Farney, W. C. (1996). Incidence of injury in texas girls' high school basketball. *The American Journal of Sports Medicine, 24*(5), 684-687.

Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., Lawrence, J. T., & Ganley, T. J. (2015). Sport-specific yearly risk and incidence of anterior cruciate ligament tears in high school athletes: A systematic review and meta-analysis. *The American Journal of Sports Medicine*, epub ahead of print.

Granan, L. P., Inacio, M. C., Maletis, G. B., Funahashi, T. T., & Engebretsen, L. (2013). Sport-specific injury pattern recorded during anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine, 41*(12), 2814-2818.

Grandstrand, S. L., Pfeiffer, R. P., Sabick, M. B., DeBeliso, M., & Shea, K. G. (2006). The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. *Journal of Strength and Conditioning Research, 20*(2), 331-335.

Grindstaff, T. L., Hammill, R. R., Tuzson, A. E., & Hertel, J. (2006). Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: A numbers-needed-to-treat analysis. *Journal of Athletic Training, 41*(4), 450-456.

Gwinn, D. E., Wilckens, J. H., McDevitt, E. R., Ross, G., & Kao, T. C. (2000). The relative incidence of anterior cruciate ligament injury in men and women at the united states naval academy. *The American Journal of Sports Medicine, 28*(1), 98-102.

Hagglund, M., Atroshi, I., Wagner, P., & Walden, M. (2013). Superior compliance with a neuromuscular training programme is associated with fewer acl injuries and fewer acute knee injuries in female adolescent football players: Secondary analysis of an rct. *British Journal of Sports Medicine*, *47*(15), 974-979.

Hamilton, R. T., Shultz, S. J., Schmitz, R. J., & Perrin, D. H. (2008). Triple-hop distance as a valid predictor of lower limb strength and power. *Journal of Athletic Training*, *43*(2), 144-151.

Harmon, K. G., & Dick, R. (1998). The relationship of skill level to anterior cruciate ligament injury. *Clinical Journal of Sport Medicine*, *8*(4), 260-265.

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (redcap)--a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform, 42*(2), 377-381.

Hashemi, J., Breighner, R., Chandrashekar, N., Hardy, D. M., Chaudhari, A. M., Shultz, S. J., . . . Beynnon, B. D. (2011). Hip extension, knee flexion paradox: A new mechanism for non-contact acl injury. *Journal of Biomechanics, 44*(4), 577-585.

Hass, C. J., Schick, E. A., Chow, J. W., Tillman, M. D., Brunt, D., & Cauraugh, J. H. (2003). Lower extremity biomechanics differ in prepubescent and postpubescent female athletes during stride jump landings. *Journal of Applied Biomechanics, 19*, 139-152.

Hass, C. J., Schick, E. A., Tillman, M. D., Chow, J. W., Brunt, D., & Cauraugh, J. H. (2005). Knee biomechanics during landings: Comparison of pre- and postpubescent females. *Medicine and Science in Sports and Exercise, 37*(1), 100-107.

Heidt, R. S., Jr., Sweeterman, L. M., Carlonas, R. L., Traub, J. A., & Tekulve, F. X. (2000). Avoidance of soccer injuries with preseason conditioning. *The American Journal of Sports Medicine, 28*(5), 659-662.

Herman, A., Botser, I. B., Tenenbaum, S., & Chechick, A. (2009). Intention-to-treat analysis and accounting for missing data in orthopaedic randomized clinical trials. *The Journal of Bone and Joint Surgery. American Volume, 91*(9), 2137-2143.

Herman, D. C., Weinhold, P. S., Guskiewicz, K. M., Garrett, W. E., Yu, B., & Padua, D. A. (2008). The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *The American Journal of Sports Medicine, 36*(4), 733-740.

Herrington, L. (2011). Knee valgus angle during landing tasks in female volleyball and basketball players. *Journal of Strength and Conditioning Research, 25*(1), 262-266.

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. V., & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *The American Journal of Sports Medicine, 27*(6), 699-706.

Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in neuromuscular control about the knee with maturation in female athletes. *The Journal of Bone and Joint Surgery. American Volume, 86-A*(8), 1601-1608.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Jr., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine, 33*(4), 492-501.

Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *The American Journal of Sports Medicine, 24*(6), 765-773.

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine, 43*(6), 417-422.

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training, 42*(2), 311-319.

Izquierdo, M., Hakkinen, K., Gonzalez-Badillo, J. J., Ibanez, J., & Gorostiaga, E. M. (2002). Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. *European Journal of Applied Physiology, 87*(3), 264-271.

Jones, P. A., Herrington, L. C., Munro, A. G., & Graham-Smith, P. (2014). Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus? *The American Journal of Sports Medicine, 42*(9), 2095-2102.

Kiani, A., Hellquist, E., Ahlqvist, K., Gedeborg, R., Michaelsson, K., & Byberg, L. (2010). Prevention of soccer-related knee injuries in teenaged girls. *Archives of Internal Medicine, 170*(1), 43-49.

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., . . . Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine*, *38*(11), 2218-2225.

Kristianslund, E., Faul, O., Bahr, R., Myklebust, G., & Krosshaug, T. (2014). Sidestep cutting technique and knee abduction loading: Implications for acl prevention exercises. *British Journal of Sports Medicine, 48*(9), 779-783.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., . . . Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *The American Journal of Sports Medicine, 35*(3), 359-367.

LaBella, C. R., Huxford, M. R., Grissom, J., Kim, K. Y., Peng, J., & Christoffel, K. K. (2011). Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: Cluster randomized controlled trial. *Archives of Pediatrics & Adolescent Medicine, 165*(11), 1033-1040.

Lephart, S. M., Abt, J. P., Ferris, C. M., Sell, T. C., Nagai, T., Myers, J. B., & Irrgang, J. J. (2005). Neuromuscular and biomechanical characteristic changes in high school athletes: A plyometric versus basic resistance program. *British Journal of Sports Medicine, 39*(12), 932-938.

Lim, B. O., Lee, Y. S., Kim, J. G., An, K. O., Yoo, J., & Kwon, Y. H. (2009). Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *The American Journal of Sports Medicine, 37*(9), 1728-1734.

Livesay, G. A., Reda, D. R., & Nauman, E. A. (2006). Peak torque and rotational stiffness developed at the shoe-surface interface: The effect of shoe type and playing surface. *The American Journal of Sports Medicine, 34*(3), 415-422.

Loomba-Albrecht, L. A., & Styne, D. M. (2009). Effect of puberty on body composition. *Current Opinion in Endocrinology, Diabetes, and Obesity, 16*(1), 10-15.

Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. F., Thomas, S. D., Griffin, L. Y., . . . Garrett, W., Jr. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *The American Journal of Sports Medicine, 33*(7), 1003-1010.

Markolf, K. L., Gorek, J. F., Kabo, J. M., & Shapiro, M. S. (1990). Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *The Journal of Bone and Joint Surgery. American Volume, 72*(4), 557-567.

Mather, R. C., 3rd, Koenig, L., Kocher, M. S., Dall, T. M., Gallo, P., Scott, D. J., . . . Spindler, K. P. (2013). Societal and economic impact of anterior cruciate ligament tears. *The Journal of Bone and Joint Surgery. American Volume, 95*(19), 1751-1759.

Matthew, D., & Delextrat, A. (2009). Heart rate, blood lactate concentration, and time-motion analysis of female basketball players during competition. *Journal of Sports Sciences, 27*(8), 813-821.

McCarthy, M. M., Voos, J. E., Nguyen, J. T., Callahan, L., & Hannafin, J. A. (2013). Injury profile in elite female basketball athletes at the women's national basketball association combine. *The American Journal of Sports Medicine, 41*(3), 645-651.

McInnes, S. E., Carlson, J. S., Jones, C. J., & McKenna, M. J. (1995). The physiological load imposed on basketball players during competition. *Journal of Sports Sciences, 13*(5), 387-397.

McLean, S. G., Huang, X., Su, A., & Van Den Bogert, A. J. (2004). Sagittal plane biomechanics cannot injure the acl during sidestep cutting. *Clinical Biomechanics, 19*(8), 828-838.

McLean, S. G., Lipfert, S. W., & van den Bogert, A. J. (2004). Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Medicine and Science in Sports and Exercise, 36*(6), 1008-1016.

McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, A. J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *British Journal of Sports Medicine, 39*(6), 355-362.

Michaelidis, M., & Koumantakis, G. A. (2013). Effects of knee injury primary prevention programs on anterior cruciate ligament injury rates in female athletes in different sports: A systematic review. *Physical Therapy in Sport, 15*(3), 200-210.

Michalsik, L. B., Madsen, K., & Aagaard, P. (2014). Match performance and physiological capacity of female elite team handball players. *International Journal of Sports Mdicine*, *35*(7), 595-607.

Mihata, L. C., Beutler, A. I., & Boden, B. P. (2006). Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: Implications for anterior cruciate ligament mechanism and prevention. *The American Journal of Sports Medicine, 34*(6), 899-904.

Mohr, M., Krustrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences, 21*(7), 519-528.

Moses, B., Orchard, J., & Orchard, J. (2012). Systematic review: Annual incidence of acl injury and surgery in various populations. *Research in Sports Medicine*, *20*(3/4), 157-179.

Mountcastle, S. B., Posner, M., Kragh, J. F., Jr., & Taylor, D. C. (2007). Gender differences in anterior cruciate ligament injury vary with activity: Epidemiology of anterior cruciate ligament injuries in a young, athletic population. *The American Journal of Sports Medicine*, *35*(10), 1635-1642.

Munro, A., Herrington, L., & Comfort, P. (2012). Comparison of landing knee valgus angle between female basketball and football athletes: Possible implications for anterior cruciate ligament and patellofemoral joint injury rates. *Physical Therapy in Sport*, *13*(4), 259-264.

Munro, A. G., & Herrington, L. C. (2011). Between-session reliability of four hop tests and the agility t-test. *Journal of Strength and Conditioning Research, 25*(5), 1470-1477.

Myer, G. D., Brent, J. L., Ford, K. R., & Hewett, T. E. (2008). A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. *British Journal of Sports Medicine, 42*(7), 614-619.

Myer, G. D., Ford, K. R., Barber Foss, K. D., Liu, C., Nick, T. G., & Hewett, T. E. (2009). The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clinical Journal of Sport Medicine, 19*(1), 3-8.

Myer, G. D., Ford, K. R., & Hewett, T. E. (2008). Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athletic Therapy Today, 13*(5), 39-44.

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2011). Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of acl injury. *British Journal of Sports Medicine, 45*(4), 245-252.

Myer, G. D., Ford, K. R., Palumbo, J. P., & Hewett, T. E. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *Journal of Strength and Conditioning Research, 19*(1), 51-60.

Myer, G. D., Sugimoto, D., Thomas, S., & Hewett, T. E. (2013). The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: A meta-analysis. *The American Journal of Sports Medicine, 41*(1), 203-215.

Myklebust, G., Engebretsen, L., Braekken, I. H., Skjolberg, A., Olsen, O. E., & Bahr, R. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: A prospective intervention study over three seasons. *Clinical Journal of Sport Medicine*, *13*(2), 71-78.

National Federation of State High School Associations. (2012). *2011-12 high school athletics participation survey*. Retrieved from http://www.nfhs.org/ParticipationStatics/PDF/2011-12%20Participation%20Survey.pdf Retrieved from http://www.nfhs.org/ParticipationStatics/PDF/2011-12%20Participation%20Survey.pdf.

Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2014). The influence of soccer playing actions on the recovery kinetics after a soccer match. *Journal of Strength and Conditioning Research, 28*(6), 1517-1523.

Noyes, F. R., Barber-Westin, S. D., Fleckenstein, C., Walsh, C., & West, J. (2005). The drop-jump screening test: Difference in lower limb control by gender and effect of neuromuscular training in female athletes. *The American Journal of Sports Medicine, 33*(2), 197-207.

Noyes, F. R., Barber-Westin, S. D., Smith, S. T., Campbell, T., & Garrison, T. T. (2012). A training program to improve neuromuscular and performance indices in female high school basketball players. *Journal of Strength and Conditioning Research, 26*(3), 709-719.

Noyes, F. R., Barber-Westin, S. D., Tutalo Smith, S. T., & Campbell, T. (2013). A training program to improve neuromuscular and performance indices in female high school soccer players. *Journal of Strength and Conditioning Research, 27*(2), 340-351.

Noyes, F. R., & Barber Westin, S. D. (2012). Anterior cruciate ligament injury prevention training in female athletes: A systematic review of injury reduction and results of athletic performance tests. *Sports Health*, *4*(1), 36-46.

O'Brien, J., & Finch, C. F. (2014). The implementation of musculoskeletal injury-prevention exercise programmes in team ball sports: A systematic review employing the re-aim framework. *Sports Medicine, 44*(9), 1305-1318.

Oiestad, B. E., Engebretsen, L., Storheim, K., & Risberg, M. A. (2009). Knee osteoarthritis after anterior cruciate ligament injury: A systematic review. *The American Journal of Sports Medicine, 37*(7), 1434-1443.

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *The American Journal of Sports Medicine, 32*(4), 1002-1012.

Olsen, O. E., Myklebust, G., Engebretsen, L., Holme, I., & Bahr, R. (2003). Relationship between floor type and risk of acl injury in team handball. *Scandinavian Journal of Medicine & Science in Sports, 13*(5), 299-304.

Olsen, O. E., Myklebust, G., Engebretsen, L., Holme, I., & Bahr, R. (2005). Exercises to prevent lower limb injuries in youth sports: Cluster randomised controlled trial. *British Medical Journal, 330*(7489), 449.

Otsuki, R., Kuramochi, R., & Fukubayashi, T. (2014). Effect of injury prevention training on knee mechanics in female adolescents during puberty. *International Journal of Sports Physical Therapy, 9*(2), 149-156.

Padua, D. A., & Distefano, L. J. (2009). Sagittal plane knee biomechanics and vertical ground reaction forces are modified following acl injury prevention programs: A systematic review. *Sports Health, 1*(2), 165-173.

Pappas, E., Nightingale, E. J., Simic, M., Ford, K. R., Hewett, T. E., & Myer, G. D. (2015). Do exercises used in injury prevention programmes modify cutting task biomechanics? A systematic review with meta-analysis. *British Journal of Sports Medicine, 49*(10), 673-680.

Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2012). Incidence of contralateral and ipsilateral anterior cruciate ligament (acl) injury after primary acl reconstruction and return to sport. *Clinical Journal of Sport Medicine, 22*(2), 116-121.

Petersen, W., Braun, C., Bock, W., Schmidt, K., Weimann, A., Drescher, W., . . . Zantop, T. (2005). A controlled prospective case control study of a prevention training program in female team handball players: The german experience. *Archives of Orthopaedic and Trauma Surgery, 125*(9), 614-621.

Pfeiffer, R. P., Shea, K. G., Roberts, D., Grandstrand, S., & Bond, L. (2006). Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *The Journal of Bone and Joint Surgery. American Volume, 88*(8), 1769-1774.

Piasecki, D. P., Spindler, K. P., Warren, T. A., Andrish, J. T., & Parker, R. D. (2003). Intraarticular injuries associated with anterior cruciate ligament tear: Findings at ligament reconstruction in high school and recreational athletes. An analysis of sex-based differences. *The American Journal of Sports Medicine, 31*(4), 601-605.

Pollard, C. D., Sigward, S. M., Ota, S., Langford, K., & Powers, C. M. (2006). The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clinical Journal of Sport Medicine, 16*(3), 223-227.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: Applications to practice* (third ed. ed.). Upper Saddle River, New Jersey: Pearson/Prentice Hall.

Powell, J. W., & Barber-Foss, K. D. (2000). Sex-related injury patterns among selected high school sports. *The American Journal of Sports Medicine, 28*(3), 385-391.

Prodromos, C. C., Han, Y., Rogowski, J., Joyce, B., & Shi, K. (2007). A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy, 23*(12), 1320-1325 e1326.

Quatman, C. E., & Hewett, T. E. (2009). The anterior cruciate ligament injury controversy: Is "valgus collapse" a sex-specific mechanism? *British Journal of Sports Medicine, 43*(5), 328-335.

Rausch, J. R., Maxwell, S. E., & Kelley, K. (2003). Analytic methods for questions pertaining to a randomized pretest, posttest, follow-up design. *Journal of Clinical Child & Adolescent Psychology, 32*(3), 467-486.

Reilly, T., & Thomas, T. (1976). A motional analysis of work-rate in different positional roles in professional football match-play. . *Journal of Human Movement Studies, 2*, 87-97.

Renstrom, P., Arms, S. W., Stanwyck, T. S., Johnson, R. J., & Pope, M. H. (1986). Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *The American Journal of Sports Medicine, 14*(1), 83-87.

Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., . . . Engebretsen, L. (2008). Non-contact acl injuries in female athletes: An international olympic committee current concepts statement. *British Journal of Sports Medicine, 42*(6), 394-412.

Rosene, J. M., Fogarty, T. D., & Mahaffey, B. L. (2001). Isokinetic hamstrings:Quadriceps ratios in intercollegiate athletes. *Journal of Athletic Training, 36*(4), 378-383.

Sakane, M., Livesay, G. A., Fox, R. J., Rudy, T. W., Runco, T. J., & Woo, S. L. (1999). Relative contribution of the acl, mcl, and bony contact to the anterior stability of the knee. *Knee Surgery, Sports Traumatology, Arthroscopy 7*(2), 93-97.

Schmikli, S. L., de Vries, W. R., Inklaar, H., & Backx, F. J. (2011). Injury prevention target groups in soccer: Injury characteristics and incidence rates in male junior and senior players. *Journal of science and medicine in sport / Sports Medicine Australia, 14*(3), 199-203.

Schmitz, R. J., Shultz, S. J., & Nguyen, A. D. (2009). Dynamic valgus alignment and functional strength in males and females during maturation. *Journal of Athletic Training, 44*(1), 26-32.

Shimokochi, Y., & Shultz, S. J. (2008). Mechanisms of noncontact anterior cruciate ligament injury. *Journal of Athletic Training, 43*(4), 396-408.

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2007). The influence of deceleration forces on acl strain during single-leg landing: A simulation study. *Journal of Biomechanics, 40*(5), 1145-1152.

Shultz, S. J., Pye, M. L., Montgomery, M. M., & Schmitz, R. J. (2012). Associations between lower extremity muscle mass and multiplanar knee laxity and stiffness: A potential explanation for sex differences in frontal and transverse plane knee laxity. *The American Journal of Sports Medicine, 40*(12), 2836-2844.

Sigward, S. M., Pollard, C. D., & Powers, C. M. (2012). The influence of sex and maturation on landing biomechanics: Implications for anterior cruciate ligament injury. *Scandinavian Journal of Medicine & Science in Sports, 22*(4), 502-509.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W., & Limroongreungrat, W. (2013a). Altered peak knee valgus during jump-landing among various directions in basketball and volleyball athletes. *Asian Journal of Sports Medicine, 4*(3), 195-200.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W., & Limroongreungrat, W. (2013b). Different sagittal angles and moments of lower extremity joints during single-leg jump landing among various directions in basketball and volleyball athletes. *Journal of Physical Therapy Science, 25*(9), 1109-1113.

Smith, H. C., Johnson, R. J., Shultz, S. J., Tourville, T., Holterman, L. A., Slauterbeck, J., . . . Beynnon, B. D. (2012). A prospective evaluation of the landing error scoring system (less) as a screening tool for anterior cruciate ligament injury risk. *The American Journal of Sports Medicine, 40*(3), 521-526.

Soderman, K., Werner, S., Pietila, T., Engstrom, B., & Alfredson, H. (2000). Balance board training: Prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. *Knee Surgery, Sports Traumatology, Arthroscopy 8*(6), 356-363.

Stanforth, P. R., Crim, B. N., Stanforth, D., & Stults-Kolehmainen, M. A. (2013). Body composition changes among female ncaa division 1 athletes across the competitive season and over a multi-year time frame. *Journal of Strength and Conditioning Research, 28*(2), 300-307.

Steffen, K., Myklebust, G., Olsen, O. E., Holme, I., & Bahr, R. (2008). Preventing injuries in female youth football--a cluster-randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports, 18*(5), 605-614.

Sugimoto, D., Myer, G. D., Foss, K. D., & Hewett, T. E. (2014). Dosage effects of neuromuscular training intervention to reduce anterior cruciate ligament injuries in female athletes: Meta- and sub-group analyses. *Sports Medicine, 44*(4), 551-562.

Taylor, J. B., Ford, K. R., Nguyen, A. D., & Shultz, S. J. (2016). Biomechanical comparison of single- and double-leg jump landings in the sagittal and frontal plane. *Manuscript submitted for publication*.

Taylor, J. B., Ford, K. R., Nguyen, A. D., Terry, L. N., & Hegedus, E. J. (2015). Prevention of lower extremity injuries in basketball: A systematic review and meta-analysis. *Sports Health, 7*(5), 392-398.

Taylor, J. B., Ford, K. R., Schmitz, R. J., Ross, S. E., Ackerman, T. A., & Shultz, S. J. (2016). Biomechanical differences in female basketball and soccer players during single- and double-leg multi-directional jump landings. *Unpublished manuscript*.

Taylor, J. B., Waxman, J. P., Richter, S. J., & Shultz, S. J. (2015). Evaluation of the effectiveness of anterior cruciate ligament injury prevention programme training components: A systematic review and meta-analysis. *British Journal of Sports Medicine, 49*(2), 79-87.

Taylor, K. A., Terry, M. E., Utturkar, G. M., Spritzer, C. E., Queen, R. M., Irribarra, L. A., . . . DeFrate, L. E. (2011). Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. *Journal of Biomechanics, 44*(3), 365-371.

Theoharopoulos, A., & Tsitskaris, G. (2000). Isokinetic evaluation of the ankle plantar and dorisflexion strength to determine the dominant limb in basketball players. *Isokinetics and Exercise Science, 8*, 181-186.

Trojian, T. H., & Collins, S. (2006). The anterior cruciate ligament tear rate varies by race in professional women's basketball. *The American Journal of Sports Medicine, 34*(6), 895-898.

Uhorchak, J. M., Scoville, C. R., Williams, G. N., Arciero, R. A., St Pierre, P., & Taylor, D. C. (2003). Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 859 west point cadets. *The American Journal of Sports Medicine, 31*(6), 831-842.

van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Medicine, 14*(2), 82-99.

Vauhnik, R., Morrissey, M. C., Rutherford, O. M., Turk, Z., Pilih, I. A., & Perme, M. P. (2009). Correlates of knee anterior laxity in sportswomen. *The Knee, 16*(6), 427-431.

Vauhnik, R., Morrissey, M. C., Rutherford, O. M., Turk, Z., Pilih, I. A., & Perme, M. P. (2011). Rate and risk of anterior cruciate ligament injury among sportswomen in slovenia. *Journal of Athletic Training, 46*(1), 92-98.

Vauhnik, R., Morrissey, M. C., Rutherford, O. M., Turk, Z., Pilih, I. A., & Pohar, M. (2008). Knee anterior laxity: A risk factor for traumatic knee injury among sportswomen? *Knee Surgery, Sports Traumatology, Arthroscopy 16*(9), 823-833.

Walden, M., Atroshi, I., Magnusson, H., Wagner, P., & Hagglund, M. (2012). Prevention of acute knee injuries in adolescent female football players: Cluster randomised controlled trial. *British Medical Journal, 344*, e3042.

Waters, E. (2012). Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: Basketball. *The Journal of Orthopaedic and Sports Physical Therapy, 42*(4), 326-336.

Weinhold, P. S., Stewart, J. D., Liu, H. Y., Lin, C. F., Garrett, W. E., & Yu, B. (2007). The influence of gender-specific loading patterns of the stop-jump task on anterior cruciate ligament strain. *Injury, 38*(8), 973-978.

Withrow, T. J., Huston, L. J., Wojtys, E. M., & Ashton-Miller, J. A. (2006). The effect of an impulsive knee valgus moment on in vitro relative acl strain during a simulated jump landing. *Clinical Biomechanics, 21*(9), 977-983.

Wojtys, E. M. (2015). Hoops news. *Sports Health, 7*(5), 390-391.

Yoo, J. H., Lim, B. O., Ha, M., Lee, S. W., Oh, S. J., Lee, Y. S., & Kim, J. G. (2010). A meta-analysis of the effect of neuromuscular training on the prevention of the anterior cruciate ligament injury in female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy 18*(6), 824-830.

Yu, B., McClure, S. B., Onate, J. A., Guskiewicz, K. M., Kirkendall, D. T., & Garrett, W. E. (2005). Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *The American Journal of Sports Medicine, 33*(9), 1356-1364.

Zakas, A., Mandroukas, K., Vamvakoudis, E., Christoulas, K., & Aggelopoulou, N. (1995). Peak torque of quadriceps and hamstring muscles in basketball and soccer players of different divisions. *The Journal of Sports Medicine and Physical Fitness, 35*(3), 199-205.

Zebis, M. K., Andersen, L. L., Brandt, M., Myklebust, G., Bencke, J., Lauridsen, H. B., . . . Aagaard, P. (2015). Effects of evidence-based prevention training on neuromuscular and biomechanical risk factors for acl injury in adolescent female athletes: A randomised controlled trial. *British Journal of Sports Medicine*, epub ahead of print.

APPENDIX A

APPROVED INSTITUTIONAL REVIEW BOARD CONSENT AND ASSENT FORMS

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

CONSENT TO ACT AS A HUMAN PARTICIPANT

Project Title: Differential Biomechanical Effects of an ACL Injury Prevention Program in Women's Basketball and Soccer Players

Principal Investigator and Faculty Advisor (if applicable): **PI**: Jeffrey B. Taylor *PT, DPT*
Faculty Advisor: Sandra Shultz, PhD

Participant's Name:

What are some general things you should know about research studies?
You are being asked to take part in a research study. Your participation in the study is voluntary. You may choose not to join, or you may withdraw your consent to be in the study, for any reason, without penalty.

Research studies are designed to obtain new knowledge. This new information may help people in the future. There may not be any direct benefit to you for being in the research study. There also may be risks to being in research studies. If you choose not to be in the study or leave the study before it is done, it will not affect your relationship with the researcher or the University of North Carolina at Greensboro. Details about this study are discussed in this consent form. It is important that you understand this information so that you can make an informed choice about being in this research study.

You will be given a copy of this consent form. If you have any questions about this study at any time, you should ask the researchers named in this consent form. Their contact information is below.

What is the study about?
This is a research project. Your participation is voluntary. This study aims to compare the biomechanical changes in women's soccer and basketball players in response to an anterior cruciate ligament (ACL) injury prevention program. In other words, the goal is to see if a standard injury prevention training program changes the way an athlete moves during their sport. Once you are enrolled, you will be randomized to a control (participate in your normal sport activities) or intervention group (participate in an injury prevention program). Participants enrolled in the control group will have the opportunity to learn the injury prevention program after the completion of the research project, if they so choose. Each participant will complete pre- and post- testing sessions, which will examine lower extremity biomechanics, knee joint laxity, and physical performance.

Why are you asking me?
You are being asked to participate in this study because you are an adolescent female basketball or soccer player. You will not be eligible for this study if you are currently suffering from a lower extremity injury, have had a lower extremity surgery in the past 6 months, or have been diagnosed with a vestibular (balance) or cardiovascular disorder.

What will you ask me to do if I agree to be in the study?
If you agree to participate and qualify for this study, you will be asked to complete pre- and post- testing sessions within one week of the onset and completion of the program, respectively. These sessions will last 60-90 minutes in duration and the following tests and procedures will be performed:

1. *Maturity and Medical/Sports Participation History.* A medical history and sport participation questionnaire will be collected from you at the pre- and post-testing session. The form will be available online via a secure REDCAP survey. These forms will yield an objective history of your sport, position, level of play, and injury history.

UNCG IRB
Approved Consent Form
Valid from:
4/9/15 to **4/8/16**

2. *Menstrual History Questionnaire.* Questions regarding your menstrual cycle, including age at menses and dates of current menstrual events will be asked of you via a secure REDCAP survey at the pre- and post- testing session.
3. *Anthropometrics.* Your anthropometrics, including height, weight, limb length, and foot structure will be recorded during both the pre- and post-test evaluation in a private setting. Body mass index (BMI) will be calculated from your height and weight measurements.
4. *Flexibility and Joint Looseness.* Your knee joint laxity will be measured with a KT-2000 arthrometer as typically done in a sports medicine professional's office. This non-invasive instrument allows researchers to measure the stability or "looseness" of your knee joint.
5. *Performance Testing.* You will complete a series of jumping and agility tasks at maximal effort. Tests will include a countermovement jump for height, triple hop tests for distance, and an agility T-test, which requires you to sprint, side-shuffle and backpedal.
6. *Motion Testing.* The motion testing session involves jumping, landing, and hopping movements. Reflective joint markers (or stickers) will be attached to your arms, trunk, hips, legs and feet with adhesive tape directly to the skin or shoes. Motion of the athlete's lower body will be recorded by digital video equipment. You will then be instructed to jump as high as you can. Jumps, landings and hops will be analyzed for joint motion, force and speed.
7. *Training Protocol.* If you are in the intervention group you will complete a 6-week training program that has been previously researched. The training program will begin one week after the pretest and consist of a combination of strength, balance, flexibility, agility and plyometric (jump) training. All training will occur at your team's normal practice facility, with a member of the research team at each session. The program should last approximately 20 minutes, and may be slightly more challenging than your typical warm-up routine, as we will ask you to do some strengthening, balance, and jumping exercises. Post-testing will be identical to the pretest and be completed one week following the last training.

If you have questions about the study. *Please contact the study Principal Investigator: Dr. Jeffrey Taylor at (336) 841-9492 or jtaylor@highpoint.edu, or Dr. Sandra Shultz at 336-3334-3027 or sjshultz@uncg.edu.*

Is there any audio/video recording?
Videos and/or photographs may be taken during the data collection or training sessions for use during future data presentations and dissemination. Your video/photo will be taken only if you provide written consent. Not allowing researchers to take video or still photography in no way influences the outcomes of the study or your ability to participate.

What are the risks to me?
The Institutional Review Board at the University of North Carolina at Greensboro has determined that participation in this study poses minimal risk to participants. The primary risks are related to potential injury from the testing and training, such as falls or with fatigue following the tests/training. However, the risk of an injury is much less than during sports play. Some muscle soreness may occur 1-2 days after testing, but should be minimal. During each of these tests an experienced researcher will be close to the participants to give proper instruction on how to perform each test.

Additionally, if you are uncomfortable with your height and weight being measured, you may ask for a research assistant of the same gender to take the measurements.

If you have any concerns about your rights, how you are being treated, concerns or complaints about this project or benefits or risks associated with being in this study please contact the Office of Research Integrity at UNCG toll-free at (855)-251-2351.

UNCG IRB
Approved Consent Form
Valid from:

4/9/15 to **4/8/16**

Are there any benefits to society as a result of me taking part in this research?
The information learned from this research study may benefit other athletes through the design of new, more effective training protocols.

Are there any benefits to *me* for taking part in this research study?
You will not receive any direct medical benefit for participating in this study. You may or may not improve strength, flexibility, power, or reduce the risk of athletic injury.

Will I get paid for being in the study? Will it cost me anything?
There are no costs to you or payments made for participating in this study.

How will you keep my information confidential?
All information obtained in this study is strictly confidential unless disclosure is required by law. All data will be stored on password protected files on password protected computers or hard drives. Once collected, all of your data will be associated with a de-identified subject number, yet a master list identifying the data will be stored in a locked, secure area in the High Point University Human Biomechanics and Physiology Lab. Absolute confidentiality of data provided through the Internet cannot be guaranteed due to the limited protections of Internet access. Please be sure to close your browser when finished, so no one will be able to see what you have been doing.

What if I want to leave the study?
You have the right to refuse to participate or to withdraw at any time, without penalty. If you do choose not to participate or withdraw, it will not affect you in any way, nor will it effect your relationship with your coach or your status on the team. If you choose to withdraw, you may request that any of your data which has been collected be destroyed unless it is in a de-identifiable state. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

What about new information/changes in the study?
If significant new information relating to the study becomes available which may relate to your willingness to continue to participate, this information will be provided to you.

Voluntary Consent by Participant:
By signing this consent form, you are agreeing that you read, or it has been read to you, and you fully understand the contents of this document and are openly willing consent to take part in this study. All of your questions concerning this study have been answered. By signing this form, you are agreeing that you are 18 years of age or older and are agreeing to participate, or have the individual specified above as a participant participate, in this study described to you by .

Please check one:
☐I allow the researchers to photograph or video record my activities during this project.
☐I do not allow researchers to photograph or video record my activities during this project.

Signature: ______________________ Date: _______________

UNCG IRB
Approved Consent Form
Valid from:

4/9/15 to **4/8/16**

Assent Template for Minors 12-18

Project Title: Differential biomechanical effects of an ACL injury prevention program in women's basketball and soccer players.

Principal Investigator: Jeffrey B. Taylor PT, DPT

<u>WHY AM I HERE?</u>

We want to tell you about a research study we are doing. Research studies are done to find better ways of helping and understanding people or to get information about how things work. In this study we want to find out more about how well injury prevention programs work in basketball and soccer players. You are being asked to be in the study because you are a healthy, women's basketball or soccer player. In a research study, only people who want to take part are allowed to do so.

<u>WHAT WILL HAPPEN TO ME IN THIS RESEARCH STUDY?</u> If it is okay with you and you agree to join this study, we will take your height and weight in a private setting. Body mass index (BMI) will be calculated from your height and weight measurements.

You can request that a male or female research assistant perform these measurements. Then, we will take measurements of your feet and the looseness of your knee like is typically done in a doctor's office. You will also be asked to walk, jump and run so that we can see how your feet and legs move. We will put stickers on your arms and legs and you will jump and run in front of special cameras that will show your picture on our computer, like a video game. We will also see how high and far you can jump, and how fast you are. Also, we will have you fill out a questionnaire on a computer to ask you about the sports you play, any injuries you may have had, and the status of your menstrual cycle. All answers will be completely confidential.

Half of the participants in this study will be asked to participate in an injury prevention program before your basketball or soccer practice. Each session will last about 20 minutes and may be slightly more challenging than your typical warm-up routine, as we will ask you to do some jumping, cutting and balance exercises.

Throughout the exercise training or testing sessions, we may take your photograph or a video of you performing various activities. You will have the right to say no to pictures and video if you prefer.

<u>HOW LONG WILL I BE IN THE RESEARCH STUDY?</u>

You will be in this study for 8 weeks. You will be asked to come to the laboratory for 2 separate testing sessions that will each last 1-2 hours.

CAN ANYTHING BAD HAPPEN TO ME?

There are only minor risks associated with this study. Like after playing sports, you may feel some muscle soreness from some of the jumping we asked you to do. There is also a possibility that you may fall during some of the exercises, but this is very uncommon.

To minimize these risks, a member of the research team will be present at all sessions and you will have access to a licensed physical therapist or athletic trainer if needed. IN order to limit the amount of muscle soreness you may have, we will do a bicycle warm-up before testing sessions to make sure your muscles are ready to work.

Sometimes the questions we ask you might seem strange or make you feel uncomfortable. If you are uncomfortable with some of the questions or prefer to speak to a research assistant of the opposite gender, please let us know and we will stop or do whatever we can to make you feel better.

CAN ANYTHING GOOD HAPPEN TO ME IN THIS RESEARCH STUDY?

We do not know if you will be helped by being in this project. However, we may learn something that will help other children prevent injuries to their knees in the future.

DO I HAVE OTHER CHOICES?

You do not have to be in this study, but there are no other alternative choices.

WHAT IF I DO NOT WANT TO BE IN THIS RESEARCH STUDY?

You do not have to be part of this project. It is up to you. You can even say okay now, but change your mind later. All you have to do is tell us. No one will be mad at you if you change your mind. Choosing not to participate will have no effect on your relationship with your coach or your status on the team.

WHAT ABOUT MY CONFIDENTIALITY?

We will do everything possible to make sure that your data and or records are kept confidential.

Unless required by law only the research team can review your study records. They are required to keep your personal information confidential.

WILL I BE PAID FOR BEING IN THIS RESEARCH STUDY?

There is no payment for participating in this research study.

DO MY PARENTS KNOW ABOUT THIS RESEARCH STUDY?

This study has been explained to your parent/parents/guardian and they have given permission for you to be in it.

WHAT IF I HAVE QUESTIONS?

You can ask *Jeff Taylor at (336) 841-9492 (jtaylor@highpoint.edu) or Sandra Shultz at (336) 334-3027 (sjshultz@uncg.edu)* anything about the study, or please call the Director in the Office Research Integrity at 336-256-1482 or 855-251-2351.

ASSENT

This study has been explained to me and I am willing to be in it.

Please check one:

☐ I allow the researchers to photograph or video record my activities during this project.

☐ I do not allow the researchers to photograph or video record my activities during this project.

____________________________________ ________________

Child's Name (printed) and Signature Date

Check which applies below *[to be completed by the person obtaining the assent]*

☐ The child is capable of reading and understanding the assent form and has signed above as documentation of assent to take part in this study.

☐ The child is not capable of reading the assent form, but the information was verbally explained to him/her. The child signed above as documentation of assent to take part in this study.

____________________________________ ________________

Signature of Person Obtaining Assent Date

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

CONSENT FOR A MINOR TO ACT AS A HUMAN PARTICIPANT: LONG FORM

Project Title: Differential biomechanical effects of an ACL injury prevention program in women's basketball and soccer players.

Principal Investigator and Faculty Advisor : **PI:** Jeffrey B. Taylor PT, DPT
Faculty Advisor: Sandra Shultz, PhD

Participant's Name:

What are some general things you should know about research studies?
Your child is being asked to take part in a research study. Your child's participation in the study is voluntary. You may choose for your child not to join, or you may withdraw your consent for him/her to be in the study, for any reason, without penalty.

Research studies are designed to obtain new knowledge. This new information may help people in the future. There may not be any direct benefit to your child for being in the research study. There also may be risks to being in research studies. If you choose for your child not to be in the study or you choose for your child to leave the study before it is done, it will not affect your relationship or your child's relationship with the researcher or the University of North Carolina at Greensboro.

Details about this study are discussed in this consent form. It is important that you understand this information so that you can make an informed choice about your child being in this research study.

You will be given a copy of this consent form. If you have any questions about this study at any time, you should ask the researchers named in this consent form. Their contact information is below.

What is the study about?
This is a research project. Your child's participation in this project is voluntary. This study aims to compare the biomechanical changes in women's soccer and basketball players in response to an anterior cruciate ligament (ACL) injury prevention program. In other words, the goal is to see if a standard injury prevention training program changes the way an athlete moves during their sport. Once your child is enrolled, they will be randomized to a control (participate in your normal sport activities) or intervention group (participate in an injury prevention program). Participants enrolled in the control group will have the opportunity to learn the injury prevention program after the completion of the research project, if they so choose. Each participant will complete pre- and post- testing sessions, which will examine lower extremity biomechanics, knee joint laxity, and physical performance.

Why are you asking my child?
Your child is being asked to participate in this study because she is an adolescent female basketball or soccer player. She will not be eligible for this study if she has a current lower extremity injury, lower extremity surgery in the past 6 months, or been diagnosed with a vestibular (balance) or cardiovascular disorder.

What will you ask my child to do if I agree to let him or her be in the study?
If you agree to let your child participate in this study, the following tests and procedures will be performed:

UNCG IRB
Approved Consent Form
Valid from:

4/9/15 to **4/8/16**

1. *Maturity and Medical/Sports Participation History.* A medical history and sport participation questionnaire will be collected from your child at the pre- and post-testing session. The form will be available online via a secure REDCAP survey. These forms will yield an objective history of your child's sport, position, level of play, and injury history.
2. *Menstrual History Questionnaire.* Questions regarding your child's menstrual cycle, including age at menses and dates of current menstrual events will be asked of your child via a secure REDCAP survey at the pre- and post- testing session.
3. *Anthropometrics.* Your child's anthropometrics, including height, weight, limb length, and foot structure will be recorded during both the pre- and post-test evaluation in a private setting. Body mass index (BMI) will be calculated from your child's height and weight measurements.
4. *Flexibility and Joint Looseness.* Your child's knee joint laxity will be measured with a KT-2000 arthrometer as typically done in a sports medicine professional's office. This non-invasive instrument allows researchers to measure the stability or "looseness" of your child's knee joint.
5. *Performance Testing.* Your child will complete a series of jumping and agility tasks at maximal effort. Tests will include a countermovement jump for height, triple hop tests for distance, and an agility T-test, which requires you to sprint, side-shuffle and backpedal.
6. *Motion Testing.* The motion testing session involves jumping, landing, and hopping movements. Reflective joint markers (or stickers) will be attached to your child's arms, trunk, hips, legs and feet with adhesive tape directly to the skin or shoes. Motion of the lower body will be recorded by digital video equipment. Your child will then be instructed to jump as high as she can. Jumps, landings and hops will be analyzed for joint motion, force and speed.
7. *Training Protocol.* If your child is in the intervention group she will complete a 6-week training program that has been previously researched. The training program will begin one week after the pretest and consist of a combination of strength, balance, flexibility, agility and plyometric (jump) training. All training will occur at her team's normal practice facility, with a member of the research team at each session. Post-testing will be identical to the pretest and be completed one week following the last training.

Each testing session will require about 1-2 hours. Intervention sessions will last for 20-25 minutes at the beginning of each team's practice.

Is there any audio/video recording of my child?
Videos and/or photographs may be taken during the data collection or training sessions for use during future data presentations and dissemination. Your child's video/photo will be taken only if you provide written consent. Not allowing researchers to take video or still photography in no way influences the outcomes of the study or your ability to participate.

What are the dangers to my child?
The Institutional Review Board at the University of North Carolina at Greensboro has determined that participation in this study poses minimal risk to participants. The primary risks are related to potential injury from the testing and training, such as falls or with fatigue following the tests/training. However, the risk of an injury is much less than during sports play. Some muscle soreness may occur 1-2 days after testing, but should be minimal. During each of these tests an experienced researcher will be close to the participants to give proper instruction on how to perform each test. Additionally, if you or your child are uncomfortable with their height and weight being measured, you may ask for a research assistant of the same gender to take the measurements.

If you have questions, want more information or have suggestions, please contact Jeff Taylor (336) 841-9492 or Sandra Shultz (336) 334-3027.

If you have any concerns about your rights, how you are being treated, concerns or complaints about this project or benefits or risks associated with being in this study, please contact the Office of Research Integrity at UNCG toll-free at (855)-251-2351.

Are there any benefits to society as a result of my child taking part in this research?
The information learned from this research study may benefit other athletes through the design of new, more effective training protocols.

Are there any benefits to *my child* as a result of participation in this research study?
Your child may not receive any direct medical benefit from participating in this study. They may or may not improve their strength, flexibility, power, or reduce the risk of athletic injury.

Will my child get paid for being in the study? Will it cost me anything for my child to be in this study?
There are no costs to you or payments made for participating in this study.

How will my child's information be kept confidential?
All information obtained in this study is strictly confidential unless disclosure is required by law. All data will be stored on password-protected files on password protected computers or hard drives. Once collected, all of your child's data will be associated with a de-identified subject number, yet a master list identifying the data will be stored in a locked, secure area in the High Point University Human Biomechanics and Physiology Lab. Absolute confidentiality of data provided through the Internet cannot be guaranteed due to the limited protections of Internet access. Please be sure to close your child closes their browser when finished, so no one will be able to see what they have been doing.

What if my child wants to leave the study or I want him/her to leave the study?
You have the right to refuse to allow your child to participate or to withdraw him or her at any time, without penalty. If your child does choose not to participate or chooses to withdraw, it will not affect your child in any way and have no effect on their relationship with their coach or her status on their team. If you or your child chooses to withdraw, you may request that any data which has been collected be destroyed unless it is in a de-identifiable state. The investigators also have the right to stop your child's participation at any time. This could be because your child has had an unexpected reaction, has failed to follow instructions, or because the entire study has been stopped.

What about new information/changes in the study?
If significant new information relating to the study becomes available which may relate to your willingness allow your child to continue to participate, this information will be provided to you.

UNCG IRB
Approved Consent Form
Valid from:

4/9/15 to **4/8/16**

Voluntary Consent by Participant:
By signing this consent form, you are agreeing that you have read it or it has been read to you, you fully understand the contents of this document and consent to your child taking part in this study. All of your questions concerning this study have been answered. By signing this form, you are agreeing that you are the legal parent or guardian of the child who wishes to participate in this study described to you by

.

Please check one:
☐I allow the researchers to photograph or video record my child's activities during this project.
☐I do not allow researchers to photograph or video record my child's activities during this project.

_________________________________ Date: ______________
Participant's Parent/Legal Guardian's Signature

UNCG IRB
Approved Consent Form
Valid from:

4/9/15 to **4/8/16**

APPENDIX B

PARTICIPANT INTAKE FORMS

Confidential

Training And Injury Form

Please complete the survey below.

Thank you!

Study ID ____________________________________

Demographics Information

First Name: ____________________________________

Last Name: ____________________________________

Today's date: ____________________________________

Email Address: ____________________________________

Date of Birth: ____________________________________

Gender:

- ☐ Female
- ☐ Male

Year in School: (select upcoming year if in-between grades)

- ☐ 6th
- ☐ 7th
- ☐ 8th
- ☐ 9th
- ☐ 10th
- ☐ 11th
- ☐ 12th
- ☐ College (Freshman)
- ☐ College (Sophomore)
- ☐ College (Junior)
- ☐ College (Senior)
- ☐ Other

Sport Participation

Sports that you have played (select all sports that you have played on an organized team)

- ☐ Baseball / Softball
- ☐ Basketball
- ☐ Cross Country
- ☐ Field Hockey
- ☐ Football
- ☐ Lacrosse
- ☐ Soccer
- ☐ Swimming
- ☐ Tennis
- ☐ Track and Field
- ☐ Volleyball
- ☐ Wrestling
- ☐ Other

Please select the grade/year in which you played the following sports:

	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	Prof
Baseball / Softball	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Basketball	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cross Country	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Field Hockey	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Football	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lacrosse	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Martial Arts	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Soccer	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Swimming	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Tennis	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Track and Field	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Volleyball	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrestling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

How many months a year do you currently play basketball?

☐ 0
☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7
☐ 8
☐ 9
☐ 10
☐ 11
☐ 12

How many days a week do you typically play basketball?

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7

What is the brand of your current basketball shoe?
(do not answer if you do not play basketball)

____

How many months a year do you currently play soccer?

☐ 0
☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7
☐ 8
☐ 9
☐ 10
☐ 11
☐ 12

How many days a week do you typically play soccer?

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5
- ☐ 6
- ☐ 7

What is the brand of your current soccer shoe/cleat? (do not answer if you don't play soccer)

____

Please choose one of the following which best describes your current activity level (Tegner & Lysolm 1985; Briggs et al. 2006)

- ☐ Level 10. Competitive sports like soccer, football, rugby at the NATIONAL ELITE level
- ☐ Level 9. Competitive sports like soccer football, rugby at LOWER divisions, OR hockey, wrestling, gymnastics
- ☐ Level 8. Competitive sports like racquetball, squash, track and field, alpine skiing
- ☐ Level 7. Competitive sports like tennis, athletics (running), handball, basketball, motorcross, cross country, track --OR-- recreational sports like soccer, football hockey, squash, athletics (jumping), cross country, track
- ☐ Level 6. Recreational sports like tennis, handball, basketball, alpine skiing, jogging 5x/wk
- ☐ Level 5. Work (Heavy Labor). --OR-- Competitive sports like cycling, cross country skiing --OR-- recreational jogging on uneven ground 2x/wk
- ☐ Level 4. Work (Moderately Heavy Labor like truck driving, etc.) --OR-- Recreational sports like cycling, cross country skiing, jogging on even ground 2x/week.
- ☐ Level 3. Work (light labor) --OR-- Competitive & Recreational sports like swimming, hiking, backpacking.
- ☐ Level 2. Work (light labor). Walking on uneven ground possible but impossible to backpack or hike
- ☐ Level 1. Work (light labor) Walking on even ground possible
- ☐ Level 0. Sick leave or disability pension because of knee problems

Over the past year, please indicate how often you performed the following activity in your healthiest state: running while playing a sport or jogging.

- ☐ Less than one time in a month
- ☐ One time in a month
- ☐ One time in a week
- ☐ 2 or 3 times in a week
- ☐ 4 or more times in a week

Over the past year, please indicate how often you performed the following activity in your healthiest state: cutting/changing directions while running

- ☐ Less than one time in a month
- ☐ One time in a month
- ☐ One time in a week
- ☐ 2-3 times in a week
- ☐ 4 or more times in a week

Over the past year, please indicate how often you performed the following activity in your healthiest state: decelerating/coming to a quick stop while running.

- ☐ Less than one time in a month
- ☐ One time in a month
- ☐ One time in a week
- ☐ 2-3 times in a week
- ☐ 4 or more times in a week

Over the past year, please indicate how often you performed the following activity in your healthiest state: pivoting/turning your body with your foot planted while playing a sport; For example: skiing, skating, kicking, throwing, hitting a ball.

- ☐ Less than one time in a month
- ☐ One time in a month
- ☐ One time in a week
- ☐ 2-3 times in a week
- ☐ 4 or more times in a week

What is the size of your current sneaker?

____

Do you wear foot orthoses? (ie. orthotics)

- ☐ Yes
- ☐ No

What type of orthotic device do you wear?

- ☐ Custom (somebody made it for you)
- ☐ Store bought (over the counter)
- ☐ Do not know

Medical and Injury History

Do you have any general health problems or illnesses? (ie. diabetes, respiratory diseases)

- ☐ Yes
- ☐ No

Please list: ______________________________

Do you have any vestibular (inner ear) or balance disorders?

- ☐ Yes
- ☐ No

Please list:

- ☐ Yes
- ☐ No

Have you ever injured your knee while playing a sport?

- ☐ Yes
- ☐ No

Which knee did you injure?

- ☐ Left
- ☐ Right
- ☐ Both
- ☐ Do not remember

What was the diagnosis of your knee injury? (you may select more than one)

- ☐ ACL tear/sprain
- ☐ PCL tear/sprain
- ☐ MCL tear/sprain
- ☐ LCL tear/sprain
- ☐ Fracture
- ☐ Dislocation
- ☐ Contusion (bruise)
- ☐ Torn cartilage (meniscus)
- ☐ Do not remember
- ☐ Other

Other knee diagnosis: ______________________________

Have you ever injured your foot or ankle while playing a sport?

- ☐ Yes
- ☐ No

Which foot/ankle did you injure?

- ☐ Left
- ☐ Right
- ☐ Both
- ☐ Do not remember

What was the diagnosis of your knee/foot injury? (you may select more than one)

- ☐ Mild sprain
- ☐ Severe sprain (significant swelling and or missed >5days)
- ☐ Fracture (including stress fracture)
- ☐ Contusion (bruise)
- ☐ Turf toe
- ☐ Plantar fasciitis
- ☐ Do not remember
- ☐ Other

Other foot/ankle diagnoses: ______________________________

Have you ever injured your hip while playing a sport?

- ☐ Yes
- ☐ No

Which hip did you injure?	☐ Left ☐ Right ☐ Both ☐ Do not remember
What was the diagnosis of your hip injury? (you may select more than one)	☐ Muscle/tendon strain ☐ Ligament sprain ☐ Bursitis ☐ Contusion (bruise) ☐ Fracture ☐ Do not remember ☐ Other
Other hip diagnoses:	______________________
Have you ever injured your back while playing a sport?	☐ Yes ☐ No
What was the diagnosis of your back injury? (you may select more than one)	☐ Muscle strain ☐ Disc injury ☐ SI joint injury ☐ Fracture (including stress fracture) ☐ Spondylolisthesis ☐ Do not remember ☐ Other
Other back diagnoses:	______________________
Have you ever had a menstrual period?	☐ Yes ☐ No
How old were you when you had your first menstrual period?	______________________
How many periods have you had in the past 12 months?	☐ 0 ☐ 1-3 ☐ 4-6 ☐ 7-12 ☐ Greater than 12
Have you ever had a head injury or concussion?	☐ Yes ☐ No
Have you ever had sugery?	☐ Yes ☐ No
Please describe your previous surgery:	______________________

FEMALE HORMONAL HISTORY

This questionnaire asks questions about your menstrual cycle. As a reminder, this information is strictly confidential. None of this information will be shared with anyone besides the study investigators. Your survey uses a coded identification number in substitution for your name. If you have any questions, or do not understand any of the questions, please let us know.

Subject Code:________________ Date:__________ Date of Birth:_______________

How old were you when you started your menstrual periods (Years of Age)? _______________

When was the first day of your last period (month/day)?______________________________

On average, how many days are there between your menstrual periods (From Day 1 of your last period to Day 1 of the next period)? ___________

How many menstrual periods have you had in the last 12 months? ____________________

Have you missed any menstrual periods within the last 12 months? (Please Circle) YES NO

Since starting your menstrual periods, has there ever been an extended time where you did not have a menstrual period (skipped periods)? (Please Circle) YES NO

If YES, when was the most recent, and for how long?

Most recent missed period: (month/day/year) ______________________________

How many months did you skip your period? _______________

Do you know when your next menstrual period will start (month/day)? __________________

Do you experience premenstrual symptoms (Please Circle)? YES NO

If you experience premenstrual symptoms, please indicate the severity of each on a scale of 0-10:

0 (None) **5 (Moderate)** **10 (Severe)**

Rate all that apply:

Bloating:	________	Spotting:	_______
Irritability:	________	Mood Swings:	_______
Food Cravings:	________	Cramps:	_______
Headache:	________	Back Pain:	_______
Other:	_______________		

Are you *currently* taking hormones (e.g. birth control pills, estrogen therapy, etc) for any reason? (Please Circle) YES NO

APPENDIX C

DESCRIPTIVE STATISTICS OF SECONDARY DATA

Appendix C1. Mean ± standard deviations for arch height index measures at pre-testing sessions.

		All Participants	**Basketball**	**Soccer**
	Intervention	0.37±0.06	0.34±0.08	0.38±0.03
Arch Height Index (seated) - right	Control	0.37±0.02	0.36±0.03	0.37±0.02
	Total	0.37±0.05	0.35±0.06	0.38±0.03
	Intervention	0.34±0.04	0.32±0.04	0.35±0.03
Arch Height Index (standing) – right	Control	0.34±0.03	0.32±0.03	0.34±0.02
	Total	0.34±0.03	0.32±0.03	0.34±0.03
	Intervention	0.36±0.03	0.35±0.03	0.37±0.03
Arch Height Index (seated) - left	Control	0.36±0.03	0.35±0.03	0.36±0.03
	Total	0.36±0.03	0.35±0.03	0.37±0.03
	Intervention	0.32±0.03	0.31±0.03	0.33±0.03
Arch Height Index (standing) - left	Control	0.32±0.03	0.31±0.03	0.33±0.02
	Total	0.32±0.03	0.31±0.03	0.33±0.02

Appendix C2. Mean ± standard deviations for anterior and posterior knee laxity measures.

		All Participants		Basketball		Soccer	
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Anterior Knee Laxity – right (mm)	Intervention	6.3±2.1	6.0±2.0	6.4±2.7	6.7±2.5	6.1±1.5	5.5±1.4
	Control	5.6±1.5	5.8±1.8	5.3±1.5	5.4±1.7	5.8±1.5	6.3±1.8
	Total	5.9±1.8	5.9±1.9	5.9±2.2	6.1±2.2	6.0±1.5	5.9±1.7
Posterior Knee Laxity – right (mm)	Intervention	2.3±0.7	2.3±0.6	2.3±1.0	2.2±0.7	2.3±0.5	2.4±0.5
	Control	2.5±0.7	2.4±0.6	2.3±0.6	2.3±0.4	2.6±0.7	2.6±0.7
	Total	2.4±0.7	2.4±0.6	2.3±0.8	2.2±0.6	2.4±0.6	2.5±0.6
Anterior Knee Laxity – left (mm)	Intervention	6.5±1.6	6.5±1.8	6.6±1.8	6.9±2.1	6.5±1.4	6.3±1.4
	Control	6.6±1.8	6.8±2.1	6.4±1.8	6.4±1.9	6.7±1.8	7.3±2.2
	Total	6.5±1.7	6.7±2.0	6.5±1.8	6.6±2.0	6.6±1.6	6.9±1.9
Posterior Knee Laxity – left (mm)	Intervention	2.5±0.9	2.3±0.6	2.4±1.1	2.4±0.6	2.5±0.5	2.3±0.7
	Control	2.4±0.5	2.4±0.6	2.6±0.5	2.5±0.6	2.3±0.5	2.3±0.6
	Total	2.4±0.7	2.4±0.6	2.5±0.9	2.4±0.6	2.4±0.5	2.3±0.6

Appendix C3. Mean ± standard deviations for performance measures.

		All Participants		Basketball		Soccer	
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Triple Hop Distance – right (inches)	Intervention	169.7±22.2	163.4±23.8	162.1±23.3	159.4±27.2	176.2±19.3	167.0±21.2
	Control	176.1±23.8	166.2±27.6	181.0±29.6	178.0±32.4	172.4±18.0	160.0±20.5
	Total	172.9±23.1	164.8±25.7	171.1±27.9	168.2±30.8	174.3±18.6	163.2±20.9
Triple Hop Distance – left (inches)	Intervention	168.6±20.5	162.4±21.5	161.0±23.0	157.8±23.3	175.2±15.8	167.0±20.1
	Control	176.7±24.5	168.4±27.6	178.8±29.2	177.9±29.6	175.0±20.7	164.2±23.4
	Total	172.6±22.8	165.5±24.9	169.5±27.4	167.5±28.0	175.1±18.3	165.5±21.8
Agility T-Test (sec)	Intervention	14.9±1.8	14.6±1.4	15.3±1.7	15.1±0.7	14.7±1.9	14.1±0.8
	Control	14.6±0.9	14.4±1.1	14.3±1.1	14.6±1.5	14.7±0.7	14.4±0.6
	Total	14.8±1.4	14.5±1.2	14.9±1.5	14.9±1.6	14.7±1.4	14.3±0.7